Ultrahigh Energy Neutrinos as Probes of New Physics**

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- Astrophysical Sources of Ultra-High Energy Neutrinos
- Studying $\nu_\mu \to \nu_\tau$ Oscillations with UHE Neutrinos
- Distinctive Energy and Nadir Angle Dependence of the Upward ν_τ Flux
- Detection of Tau Neutrinos with km^3 Detectors
- Ultrahigh Energy Neutrinos as Probes of New Physics

S. Iyer, M.H. Reno and I. Sarcevic, Phys. Rev. **D61, 053003 (2000); S. Iyer Dutta, M.H. Reno and I. Sarcevic, Phys. Rev. **D62**, 123001 (2000); S. Iyer Dutta, M.H. Reno, D. Seckel and I. Sarcevic, Phys. Rev. **D63**, 094020 (2001); S. Iyer Dutta, M.H. Reno and I. Sarcevic, Phys. Rev. **D64**, 113001 (2001); Phys. Rev. **D66**, 077302 (2002); Phys. Rev. **D66**, 033002 (2002); I. Mocioiu, Y. Nara and I. Sarcevic, Phys. Lett. **B557**, 87 (2003); S. Iyer Dutta, I. Mocioiu, J. Jones, M.H. Reno and I. Sarcevic, in preparation.

- Since neutrinos are highly stable, neutral particles cosmic neutrinos point back to astrophysical point sources and bring information from processes otherwise obscured by a few hundred gm of a material.

- Interaction length of a neutrino is

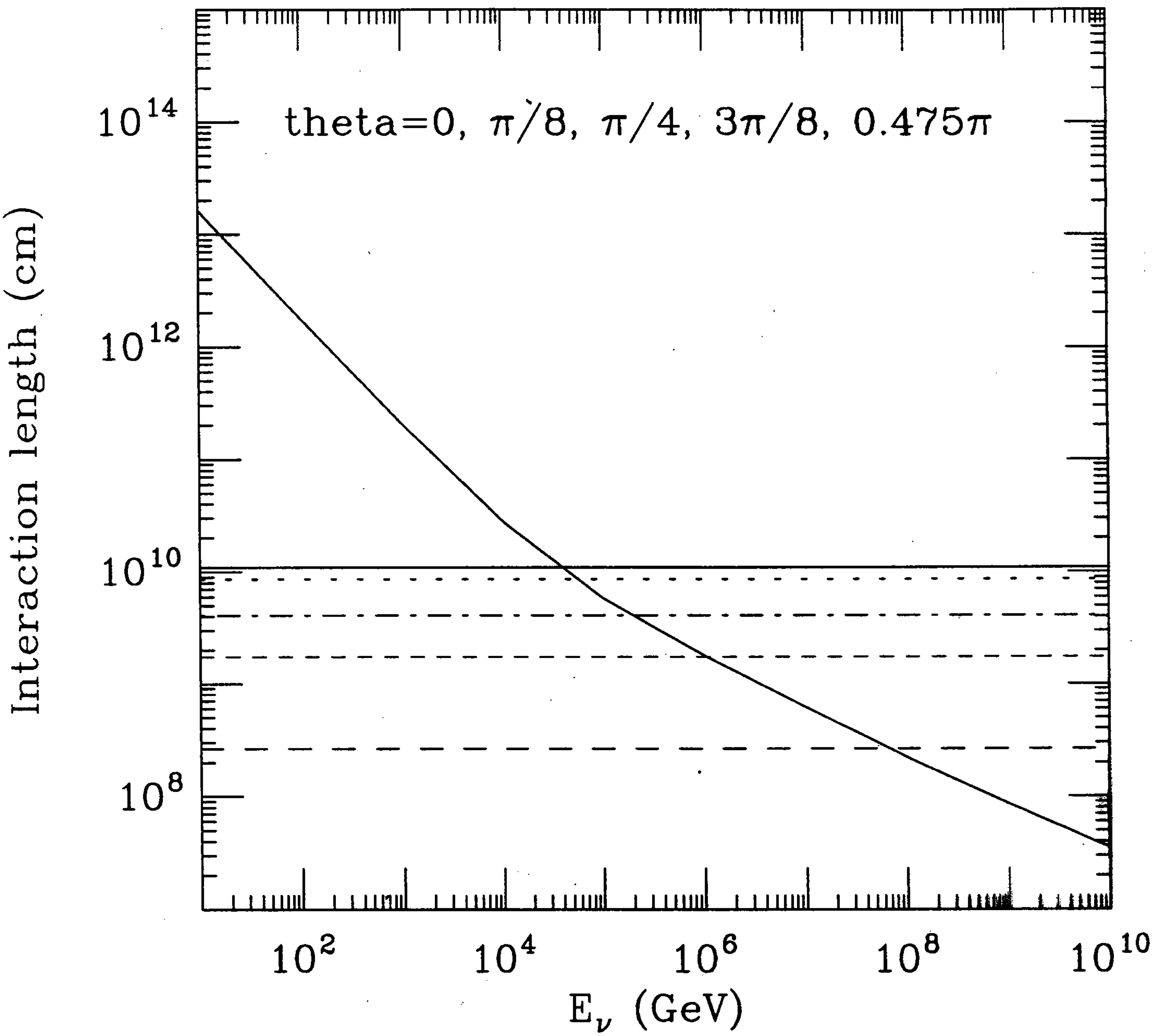
$$\mathcal{L}_{\text{int}} \equiv \frac{1}{\sigma \cdot N_A}$$

Interaction length of 1TeV neutrino is 250 kt/cm^2 or column of water of 2.5 million km deep.

- Neutrino astronomy could provide a unique window into the deepest interiors of stars and galaxies, while HE photons get absorbed by a few hundred gm of a material.

- UHE Neutrinos could also provide unique probe of physics beyond the Standard Model.

NEUTRINO INTERACTION LENGTH



ATMOSPERE : 10^3 cm w.e. VERTICAL
3.6×10^4 cm w.e. HORIZONTAL

Sources of UHE Neutrinos

- Cosmogenic Neutrinos

  Neutrinos produced by high energy cosmic rays interacting with the microwave background radiation (photoproduction followed by pion decay).

- Neutrinos from AGNs

  AGNs are believed to be prodigious particle accelerators and the most powerful radiation sources known in the Universe, with luminosities ranging from $10^{42} - 10^{48}$erg/s. If the observed TeV **gamma rays** (from **Mkn 421** and **Mkn 501**) originate in the decay of π^0, then AGNs may also be the most powerful sources of UHE neutrinos.

- Neutrinos from GRBs

  The cosmological GRB fireball energy is expected to be converted by photo-meson production to a burst of high energy neutrinos.

- Neutrinos from Topological Defects

  Topological Defects formed in the Early Universe are believed to be non-accelerator sources of UHE neutrinos. In the TD models neutrinos are produced dirtectly at UHEs by the cascades initiated by the decay of a supermassive elementary "X" particle associated with some Grand Unified Theory (GUT), rather than being accelated. The X particle are usually thought to be released from topological monopoles left over from GUT phase transition and it decays into quarks, gluons, leptons.

- The observed photon energy spectrum is a power-law:

$$\frac{dN_\gamma}{dE_\gamma} \approx E_\gamma^{-2}$$

for 100MeV$\leq E_\gamma \leq 2TeV$

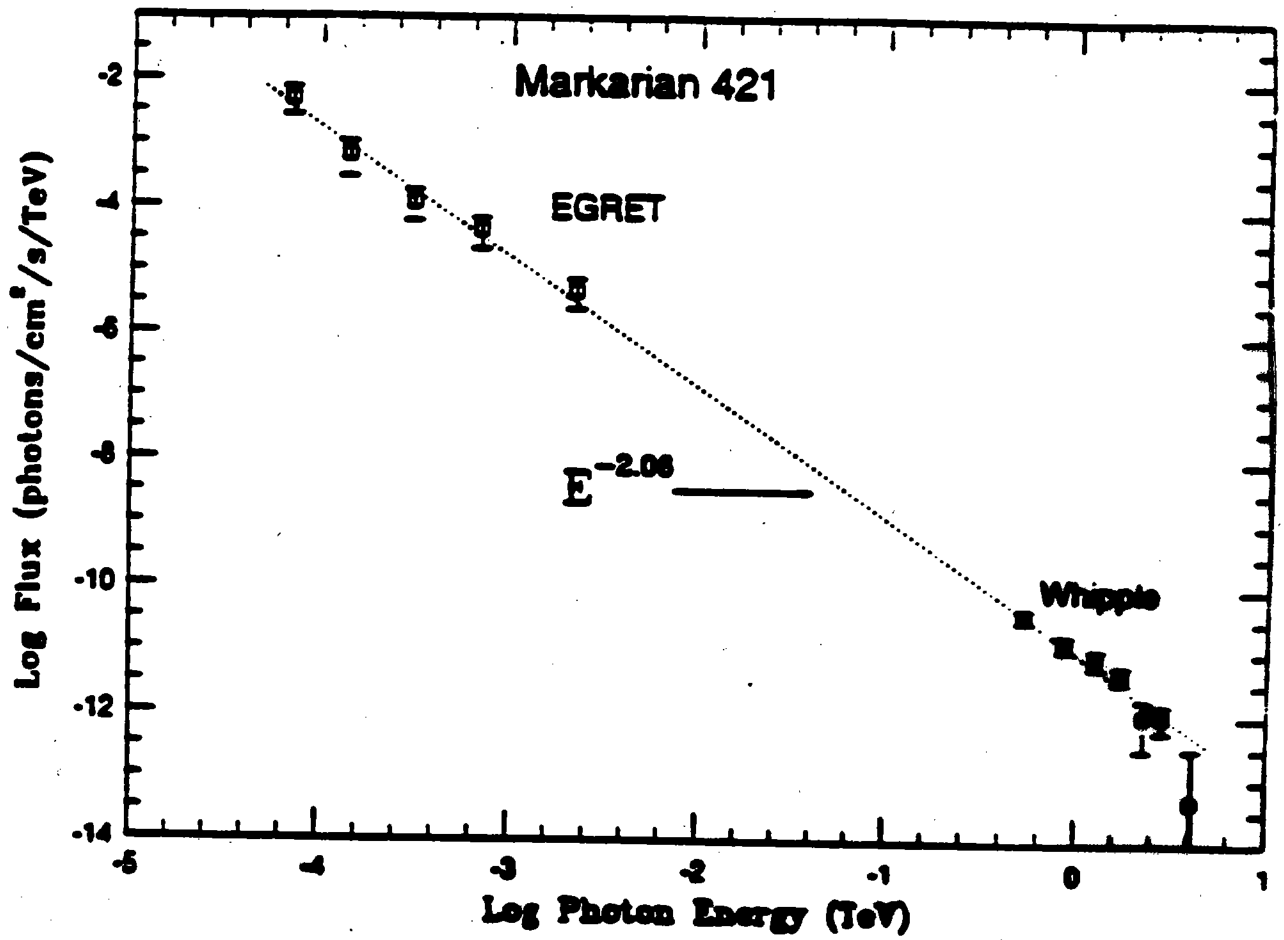
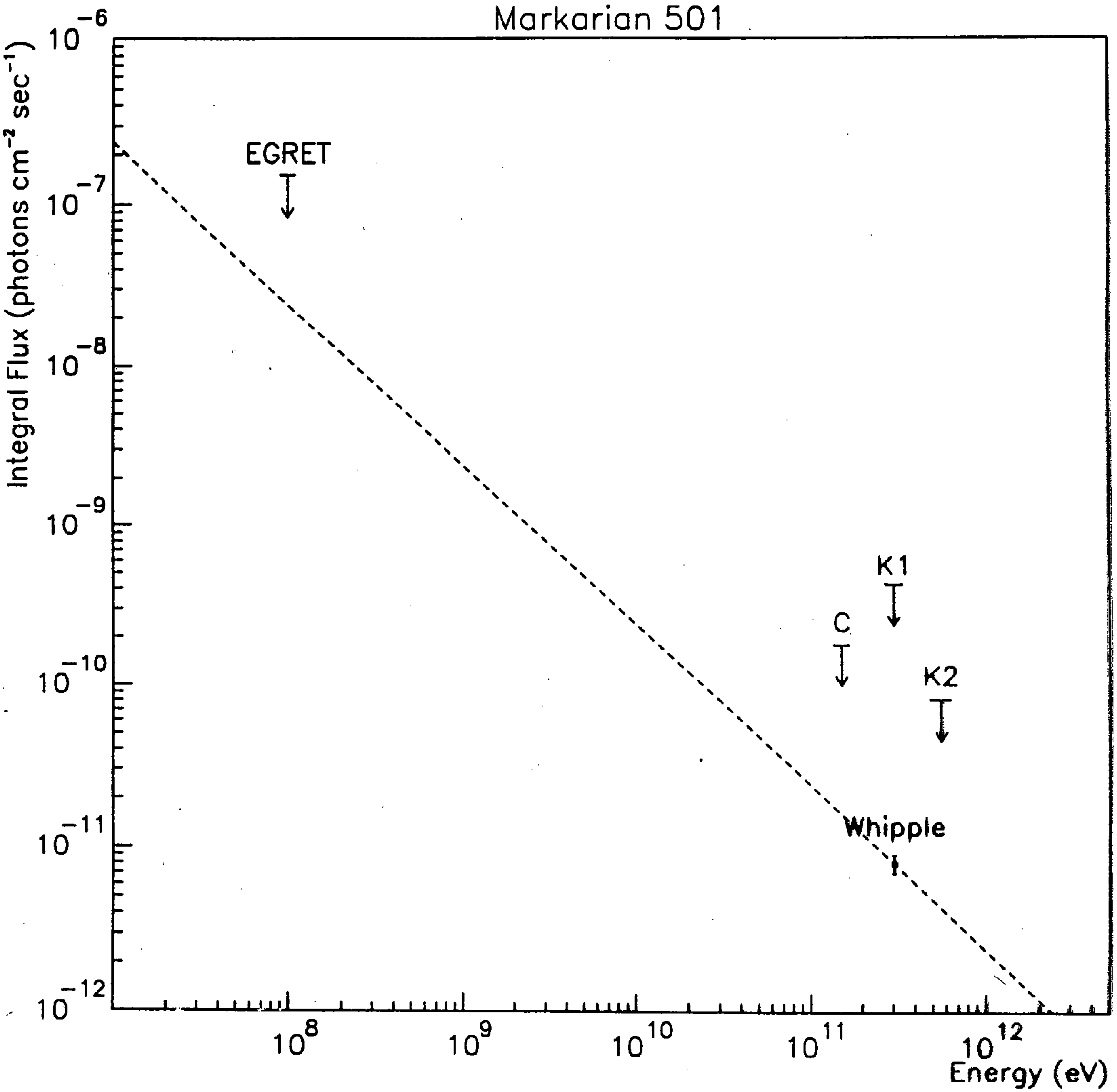


Figure 2. Differential energy spectrum from both the EGRET (Lin *et al.* 1992 and Whipple observations of Markarian 421. The EGRET observations wer taken 27 June - 11 July, 1991; the Whipple observations 24 March - 2 June 1992. A single power-law, with energy exponent 2.06 ± 0.04, is an acceptabl description of the combined dataset. Possible systematic errors in the exponen are not included. They are difficult to estimate because of the differing techniqu by which the fluxes have been measured and because of the non-contemporaneou nature of the observations.

Courtesy of T.C. Weekes (Whipple)



T.C. Weekes (Whipple)

Table 1.

Nearby Bl Lac Objects (out to z= 0.11).

Object	Alias	z	EGRET 100 MeV ($10^{-7}cm^{-2}s^{-1}$)	FLWO 300 GeV (Whipple)	Alpha OX/ Alpha RO
1101+384	Mrk421	0.031	1.4±0.4	Detected	1.14/0.42
1652+398	Mrk501	0.034	<1.5	Detected	1.15/0.48
1ES2344+514		0.044	?	Detection?	1.18/0.41 ApJ 501 (98)
1113+704	Mrk 180	0.046	<0.4	Upper limit	1.27/0.35
1ES1959+650		0.048	?	Upper limit	1.19/0.32
1514-241	Ap Lib	0.049	<1.0	S.H.	
1807+698	3C371	0.050	<0.9	Upper limit	1.72/0.50
0521-365	PKS	0.055	1.8±0.5	S.H.	
1727+502	I Zw 187	0.055	<0.8	Upper limit	1.01/0.47
1ES2321+419		0.059	?	Upper limit	1.19/0.32
0548-322	PKS	0.069	<1.0	S.H.	1.02/0.39
2200+420	Bl Lac	0.069	Detected	Upper limit	1.31/0.61
2005-489	PKS	0.071	1.8±0.5	S.H.	1.11/0.53
1ES1741+196		0.083	?	Not yet observed	1.18/0.41
1219+285	W COM	0.102	0.8±0.2	Upper limit	1.27/0.61

- It seems plausible that protons generated within an AGN interact with matter or radiation in the AGN disk, or with UV photons in the associated jets, to produce pions whose decay products include PHOTONS and NEUTRINOS

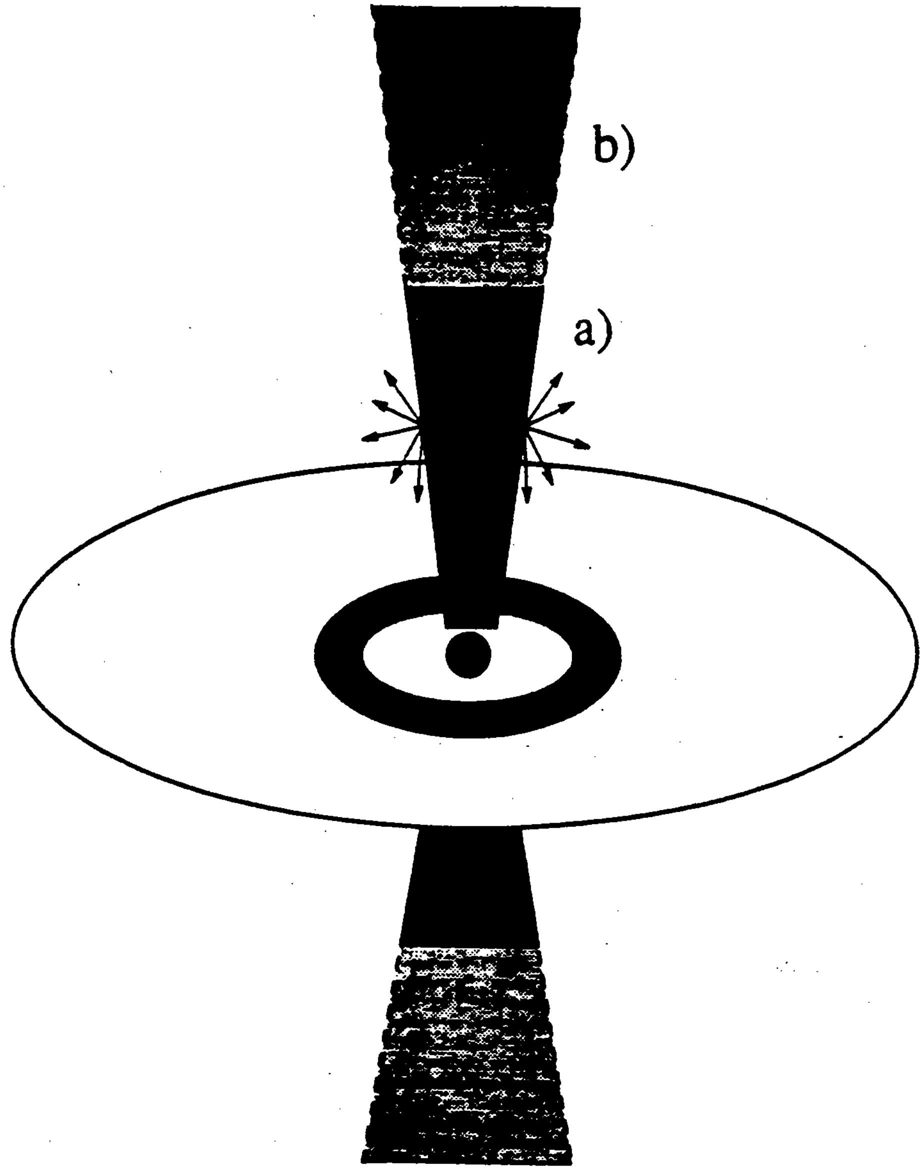


FIG. 1. Schematic diagram of the central engine of an AGN (not to scale). A supermassive black hole at the center is surrounded by an accretion disk of gas falling into the black hole. Two jets of plasma are ejected perpendicular to the disk. Typically, shocks form in the jets. In such shocks (wavy line), protons are accelerated, which eventually leave the jet and drift back to the disk. In the inner region (dark ring, $\approx 10R_S$ to $\approx 200R_S$), protons reaching the disk initiate cascades through pp interactions. Only protons accelerated in the outer region (b) of the jet can reach energies above the threshold for $p\gamma$ reactions with UV photons.

Gamma Ray Bursts (GRBs)

- Fireball Model: GRB are produced by the dissipation of the kinetic energy of the relativistic expanding fireball with a large fraction ($> 10\%$) of fireball energy being converted by photo-pion production to HE neutrinos. HE protons accelerated in ultrarelativistic shocks interact with synchrotron photons inside the fireball.

$$F^{s}_{\nu+\bar{\nu}}(E) = 4.0 \times 10^{-\alpha} E^{-n},$$

where $\alpha = 13$ and $n = 1$ for $E < 10^5$ GeV and $\alpha = 8$, $n = 2$ for $10^5 < E < 10^7$ GeV and $n = 3$ for $E > 10^7$ GeV.

Waxman-Bahcall, *Phys. Rev.* **D59**, 023002 (1999)

- Recently another mechanism was proposed for producing TeV neutrinos, from choked relativistic fireball jets that are unable to punch through the stellar envelope. These neutrinos appear as precursor signal, tens of seconds prior to the observations of γ rays produced outside the star by a collapsing massive star induced GRB. The predicted neutrino flux is given by:

$$F^{s}_{\nu+\bar{\nu}}(E) = 10^{-7} E^{-2}$$

Meszaros and Waxman, PRL **87** (2001)

Neutrinos from Topological Defects

- Topological defects: monopoles, cosmic strings, domain walls, and superconducting cosmic strings, might have been formed in symmetry-breaking phase transitions in the early Universe.
  - ⋆ In the so-called "top-down" (TD) models, γ-rays, electrons (positrons), and neutrinos are produced dirtectly at UHEs by the cascades initiated by the decay of a supermassive elementary "X" particle associated with some Grand Unified Theory (GUT), rather than being accelated (i.e. TD might constitute a "nonacceleration" source of UHE neutrinos). The X particle are usually thought to be released from topological monopoles left over from GUT phase transition and it decays into quarks, gluons, leptons.
- Predicted spectra are much harder and extend much further beyond 100EeV than shock acceleration spectra.
- TD might be resonsible for the highest energy events observed ($E \sim 10^{21}$eV) $\rightarrow$ Fly's Eye and AGASA Experiments (Fig.)

Topological Defects Models:

Sigl-Lee-Schramm-Coppi (SLSC)

Wichoski-MacGibbon-Brandenberger (WMB)

- Energy loss of the string network converted into gravitational radiation or particle production
- Upper limits from cosmic ray data (Frejus, Fly's Eye)
- Upper limit for strong source evolution

$$2 \times 10^{-8} E^{-2}$$

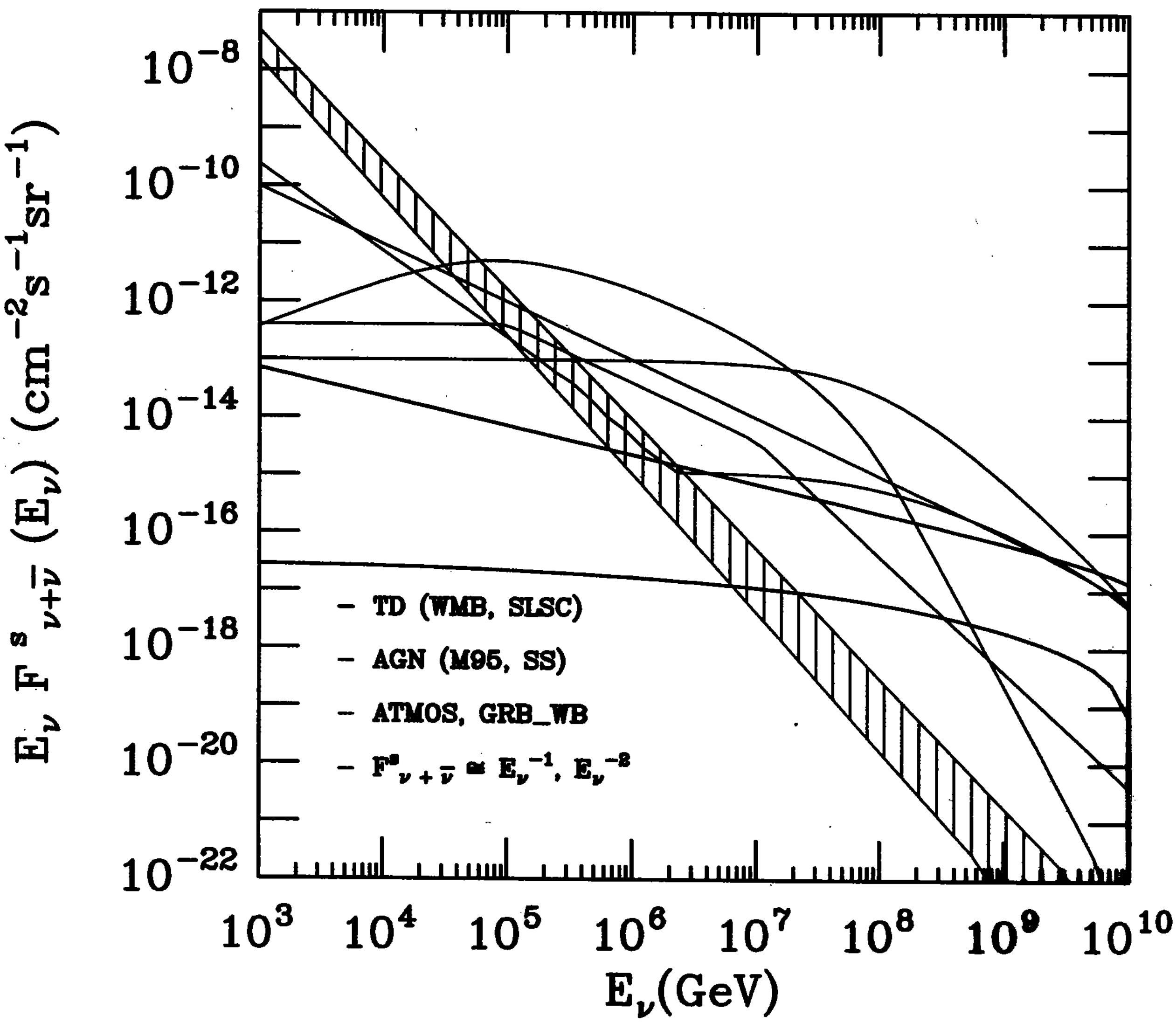
AGN_SS flux $\rightarrow$ upper bound for AGN core emission

(difusse X-ray background)

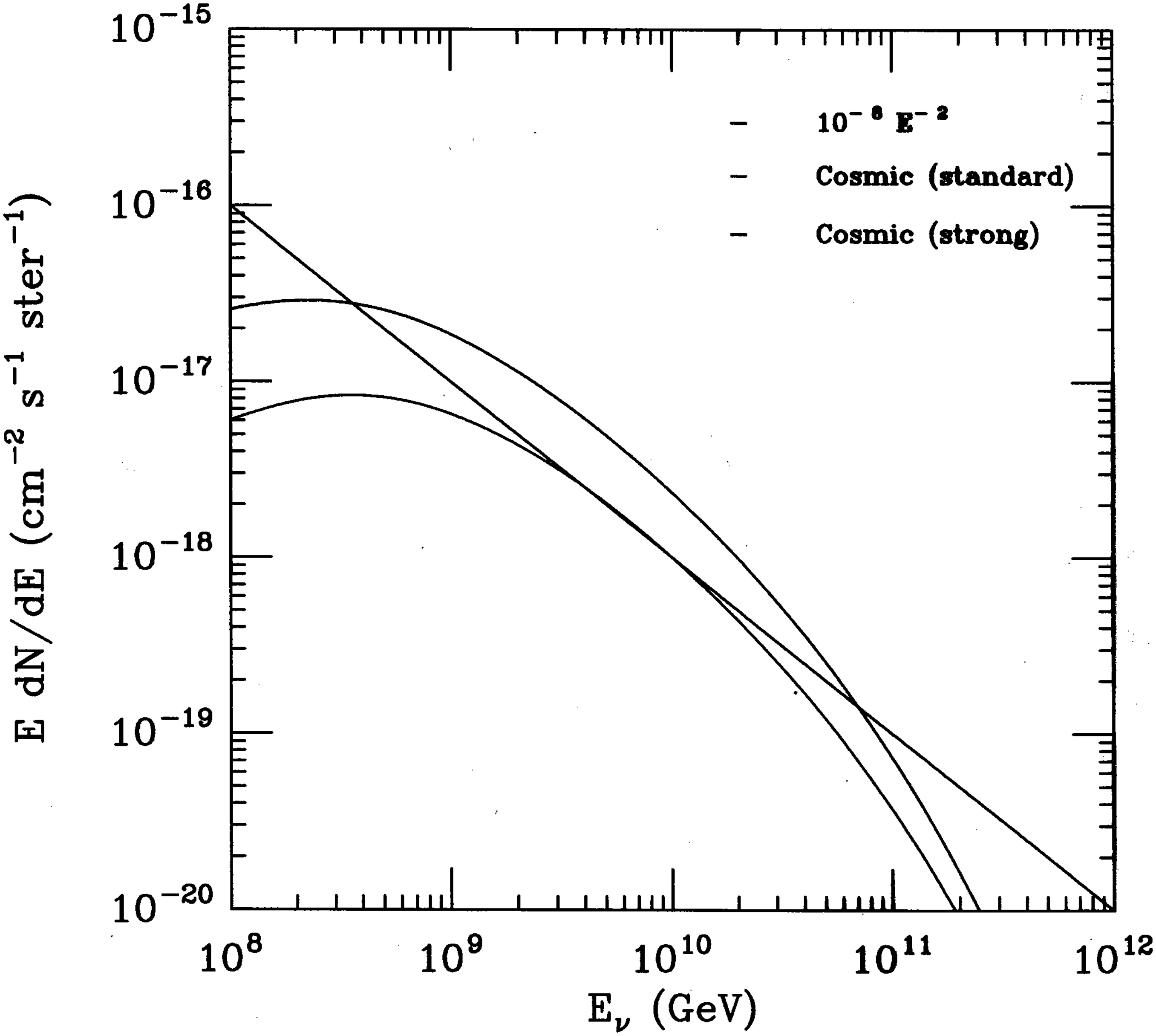
flux above 1 PeV may be reduced due to cooling of pions and muons in the strong magnetic fields of AGN

M_95A flux $\rightarrow$ upper bound for AGN jet emission model

(extragalactic γ-ray background)



10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
$E_\nu\ F^s_{\nu+\bar{\nu}}\ (E_\nu)\ (cm^{-2}s^{-1}sr^{-1})$
– TD (WMB, SLSC)
– AGN (M95, SS)
– ATMOS, GRB_WB
– $F^s_{\nu+\bar{\nu}} \cong E_\nu^{-1}, E_\nu^{-2}$
10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10}
E_ν(GeV)



$10^{-8}\ E^{-2}$
Cosmic (standard)
Cosmic (strong)
E dN/dE (cm^{-2} s^{-1} ster^{-1})
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
E_ν (GeV)

Neutrino Oscillations with 1000 Megaparsec Baseline

- Basic processes of neutrino production in extragalactic sources:

$$p + \gamma \rightarrow n + \pi^+$$
$$\hookrightarrow n + \gamma \rightarrow p + \pi^-$$
$$\hookrightarrow \pi^\pm \rightarrow \mu^\pm + \nu_\mu$$
$$\hookrightarrow \mu^\pm \rightarrow e^\pm + \nu_\mu + \nu_e$$

$$p + \gamma \rightarrow p + \pi^o$$
$$\hookrightarrow \pi^o \rightarrow \gamma\gamma$$

- For astronomical distances ($L \sim 1000 Mpc$) and with $\Delta m^2 \sim 10^{-3} eV^2$

$$< \sin^2(\frac{1.27\Delta \mathrm{m}^2 \mathrm{L(Km)}}{\mathrm{E(GeV)}}) >= \frac{1}{2}$$

(For PeV neutrinos potentially sensitive to $\Delta \mathrm{m}^2 \sim 10^{-17} \mathrm{eV}^2$!)

- The probability for $\nu_\mu \rightarrow \nu_\tau$ oscillations is given by

$$P(\nu_\mu \rightarrow \nu_\tau; L) = \sin^2 2\theta \ \sin^2(\frac{1.27\Delta \mathrm{m}^2 \mathrm{L(Km)}}{\mathrm{E(GeV)}})$$

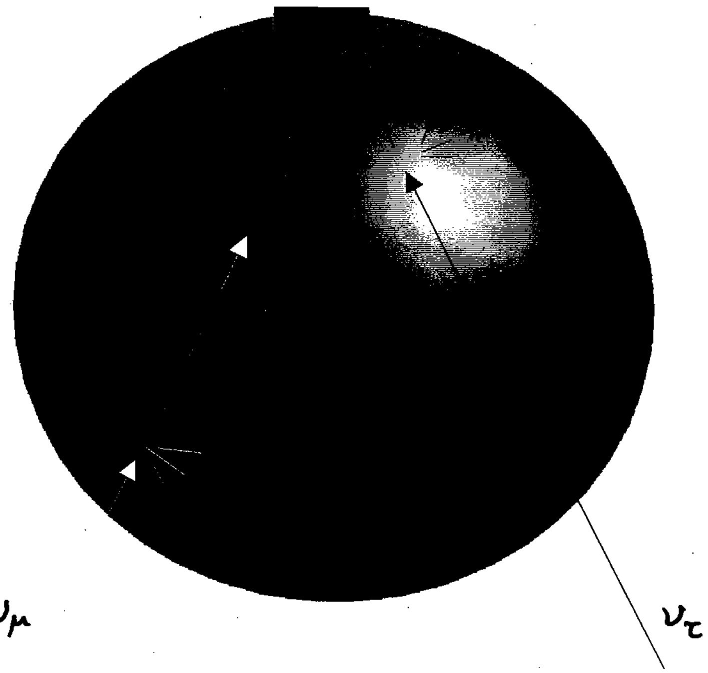
- For large mixing angles, $P(\nu_\mu \rightarrow \nu_\tau; L) = 1/2$, i.e. $F_{\nu_\mu} = F_{\nu_\tau}$

- Qualitative behavior of ν_τ is different than ν_μ in propagation through Earth (Halzen and Saltzberg, PRL 81 (1998))

- Main difference due to lifetimes:

$$\tau_\mu = 2.2 \times 10^{-6} s$$

$$\tau_\tau = 2.9 \times 10^{-13} s$$



ν_μ
ν_τ

- As ν_μ's propagate through the Earth, their flux get attenuated while ν_τ's get regenerated via τ decay

$$\nu_\mu + N \to \mu + X$$

and muons get absorbed, while

$$\nu_\tau + N \to \tau + X$$

followed by the τ decaying back into ν_τ

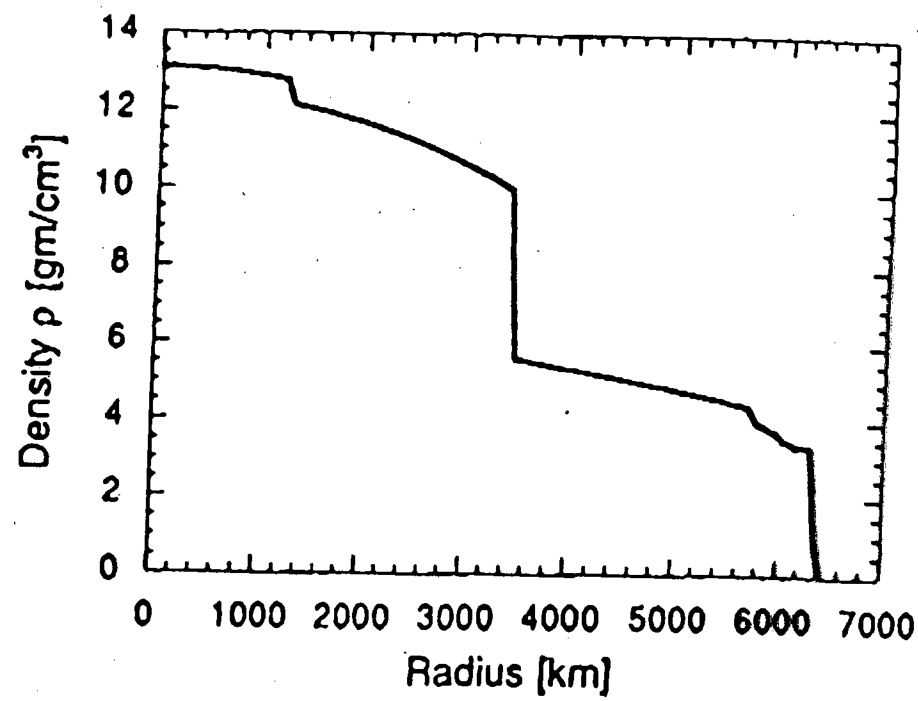
$$\tau \to \nu_\tau + X$$

(muon lifetime: $\tau_\mu = 2.2 \times 10^{-6} s$)
(tau lifetime: $\tau_\tau = 2.9 \times 10^{-13} s$)

tau decay length:

$$\rho_\tau^{dec}(E, X) = \gamma \tau_\tau \rho(X)$$

- Tau charged-current interaction length and the photonuclear interaction length become comparable to the tau decay length at $E > 10^8$ GeV



Density ρ [gm/cm³]
14
12
10
8
6
4
2
0
0
1000
2000
3000
4000
5000
6000
7000
Radius [km]

ν_μ Propagation through the Earth

- Transport equation for ν_μ

$$\frac{\partial F_{\nu_\mu}(E,X)}{\partial X} = -\frac{F_{\nu_\mu}(E,X)}{\lambda_{\nu_\mu}(E)} + \int_E^\infty dE_y \left[\frac{F_{\nu_\mu}(E_y,X)}{\lambda_{\nu_\mu}(E_y)}\right] \frac{dn}{dE}^{NC}(E_y,E)$$

where X is the column depth,

$$X = \int_0^L \rho(L')dL'$$

- Density Profile of the Earth

ν_τ Propagation through the Earth

- Coupled transport equations for the flux of ν_τ and τ:

$$\frac{\partial F_{\nu_\tau}(E,X)}{\partial X} = -\frac{F_{\nu_\tau}(E,X)}{\lambda_{\nu_\tau}(E)} + \int_E^\infty dE_y \left[\frac{F_{\nu_\tau}(E_y,X)}{\lambda_{\nu_\tau}(E_y)}\right] \frac{dn}{dE}^{NC}(E_y,E)$$

$$+ \int_E^\infty dE_y \left[\frac{F_\tau(E_y,X)}{\rho_\tau^{dec}(E_y)}\right] \frac{dn}{dE}^{dec}(E_y,E) + \int_E^\infty dE_y \left[\frac{F_\tau(E_y,X)}{\lambda_\tau(E_y)}\right] \frac{dn}{dE}^{CC}(E_y,E)$$

and for the τ's

$$\frac{\partial F_\tau(E,X)}{\partial X} = -\frac{F_\tau(E,X)}{\lambda_\tau(E)} - \frac{F_\tau(E,X)}{\rho_\tau^{dec}(E,X,\theta)}$$

$$+ \int_E^\infty dE_y \left[\frac{F_{\nu_\tau}(E_y,X)}{\lambda_{\nu_\tau}(E_y)}\right] \frac{dn}{dE}^{CC}(E_y,E) + \int_E^\infty dE_y \left[\frac{F_\tau(E_y,X)}{\lambda_\tau(E_y)}\right] \frac{dn}{dE}^{\tau\tau}(E_y,E)$$

- We include all τ decay modes with corresponding branching fraction and energy distribution

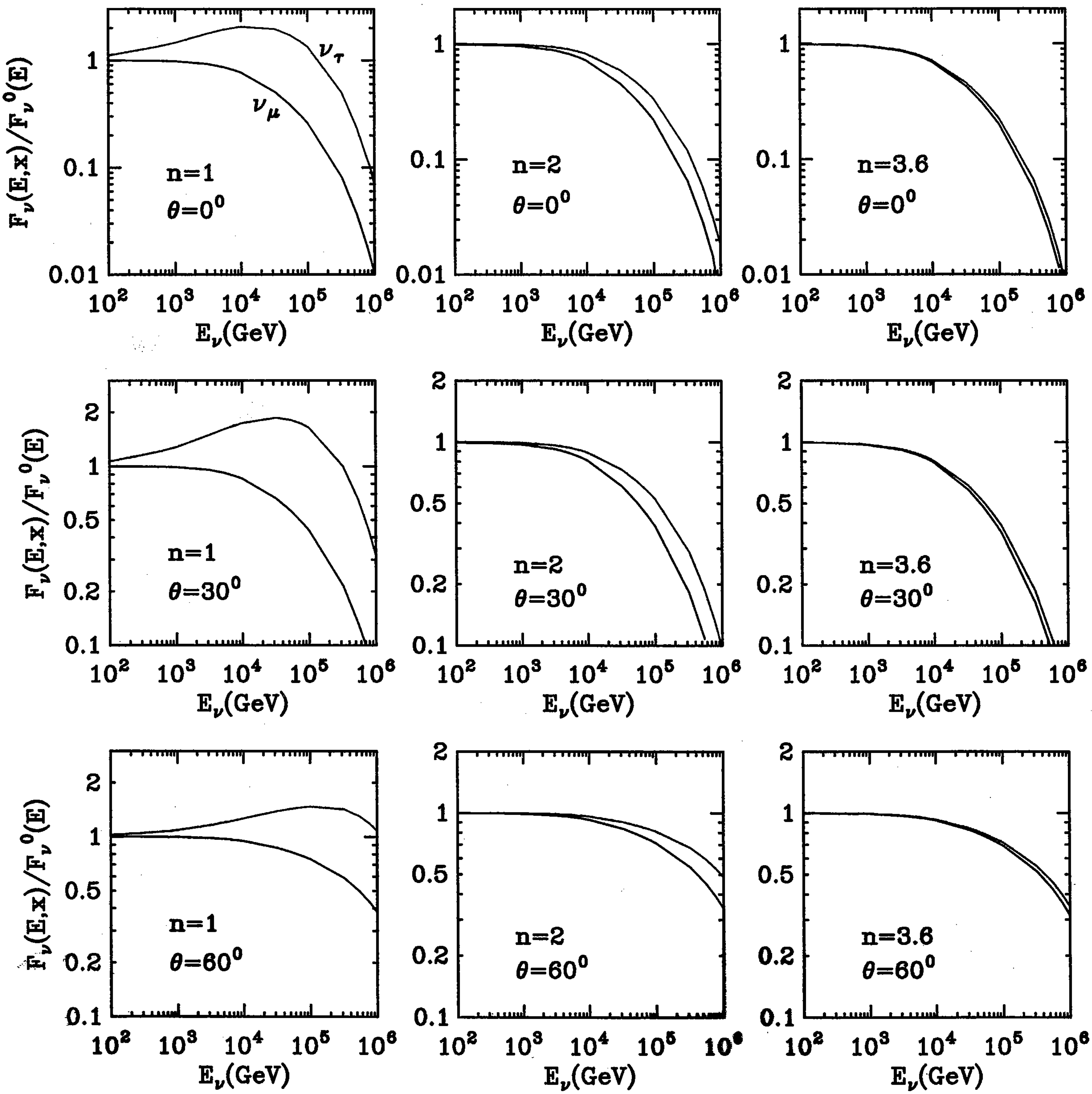
$$\tau \to \nu_\tau \mu \nu_\mu \cdots\cdots B_\tau = 0.36$$

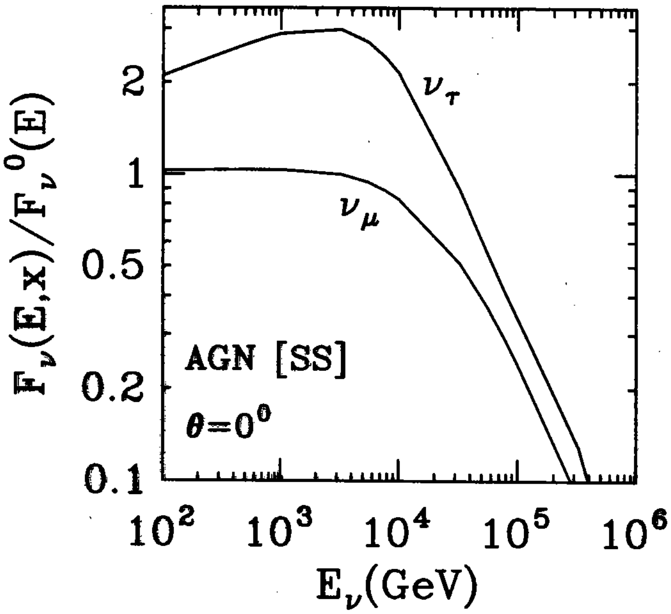
$\nu_\tau e \nu_e$

$$\tau \to \nu_\tau \pi \cdots\cdots B_\tau = 0.12$$

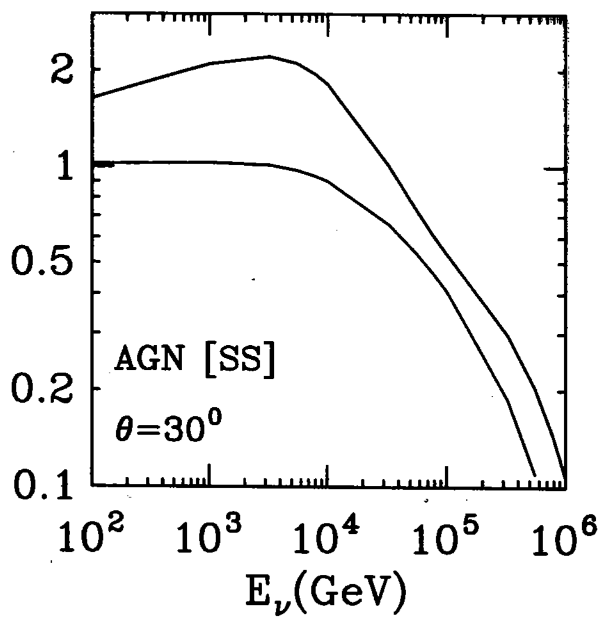
$$\tau \to \nu_\tau \rho \cdots\cdots B_\tau = 0.26$$

$$\tau \to \nu_\tau a_1 \cdots\cdots B_\tau = 0.13$$

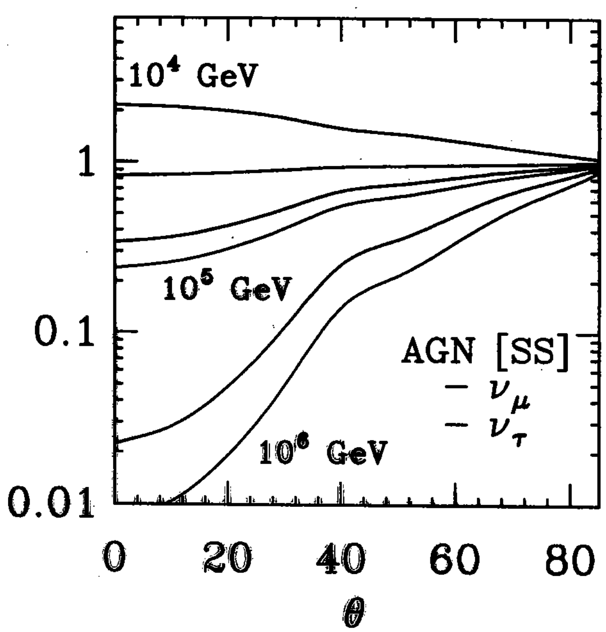

$F_\nu(E,x)/F_\nu^0(E)$
E_ν(GeV)
ν_τ
ν_μ
n=1
$\theta=0^0$
n=2
$\theta=0^0$
n=3.6
$\theta=0^0$
n=1
$\theta=30^0$
n=2
$\theta=30^0$
n=3.6
$\theta=30^0$
n=1
$\theta=60^0$
n=2
$\theta=60^0$
n=3.6
$\theta=60^0$



$F_\nu(E,x)/F_\nu{}^0(E)$
ν_τ
ν_μ
AGN [SS]
$\theta=0^0$
2
1
0.5
0.2
0.1
10^2 10^3 10^4 10^5 10^6
E_ν(GeV)



AGN [SS]
$\theta=30^0$
2
1
0.5
0.2
0.1
10^2 10^3 10^4 10^5 10^6
E_ν(GeV)

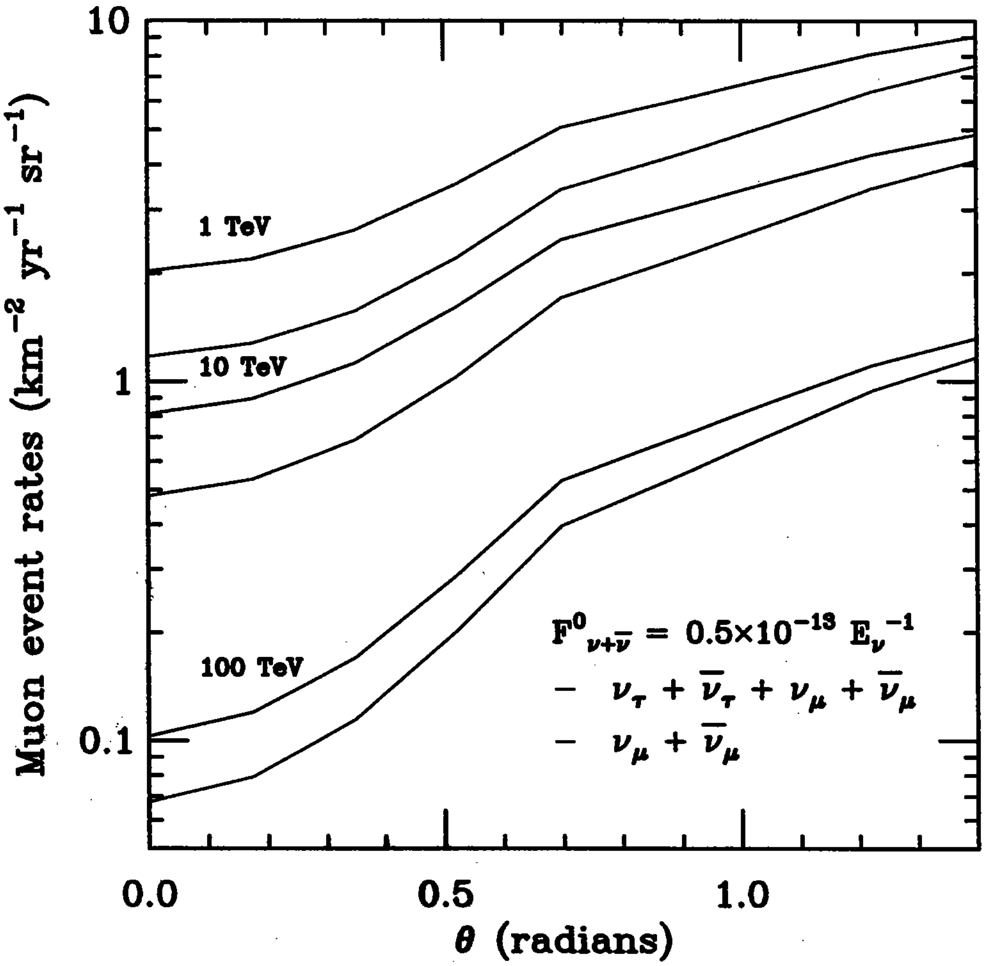


10^4 GeV
10^5 GeV
10^6 GeV
AGN [SS]
— ν_μ
— ν_τ
1
0.1
0.01
0 20 40 60 80
θ

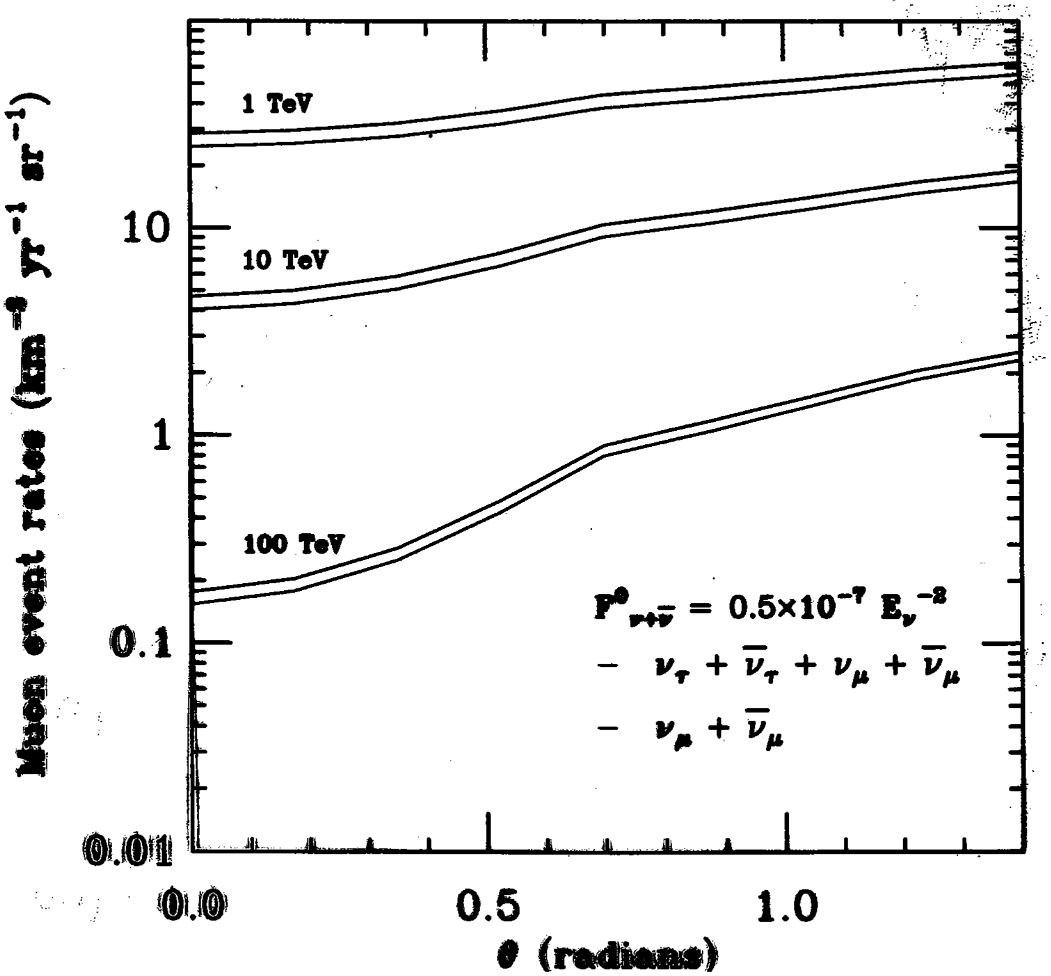
Tau Neutrino Detection

- *Upward Muons*
  - **signal :** $\nu_\tau N \to \tau X$
    $\hookrightarrow \tau \to \nu_\tau \nu_\mu \mu$
  - **background :** $\nu_\mu N \to \mu X$

- *Upward Hadronic/Electromagnetic Showers*
  - **signal :** $\nu_\tau N \to \tau X$
    $\tau \to \nu_\tau X/e$
  - **background :** $\nu_{\mu,e} N \to \nu_{\mu,e} X$
    $\nu_e N \to e X$



Muon event rates (km^{-2} yr^{-1} sr^{-1})
1 TeV
10 TeV
100 TeV
$F^0_{\nu+\bar{\nu}} = 0.5\times10^{-13}\ E_\nu^{-1}$
– $\nu_\tau + \bar{\nu}_\tau + \nu_\mu + \bar{\nu}_\mu$
– $\nu_\mu + \bar{\nu}_\mu$
θ (radians)



Muon event rates (km^{-2} yr^{-1} sr^{-1})
1 TeV
10 TeV
100 TeV
$F^0_{\nu+\bar{\nu}} = 0.5\times10^{-7}\ E_\nu^{-2}$
– $\nu_\tau + \bar{\nu}_\tau + \nu_\mu + \bar{\nu}_\mu$
– $\nu_\mu + \bar{\nu}_\mu$
θ (radians)

Is ν_τ contribution to upward muons significant?

- *For steeper fluxes ν_τ contribution is about* $20 - 25\%$

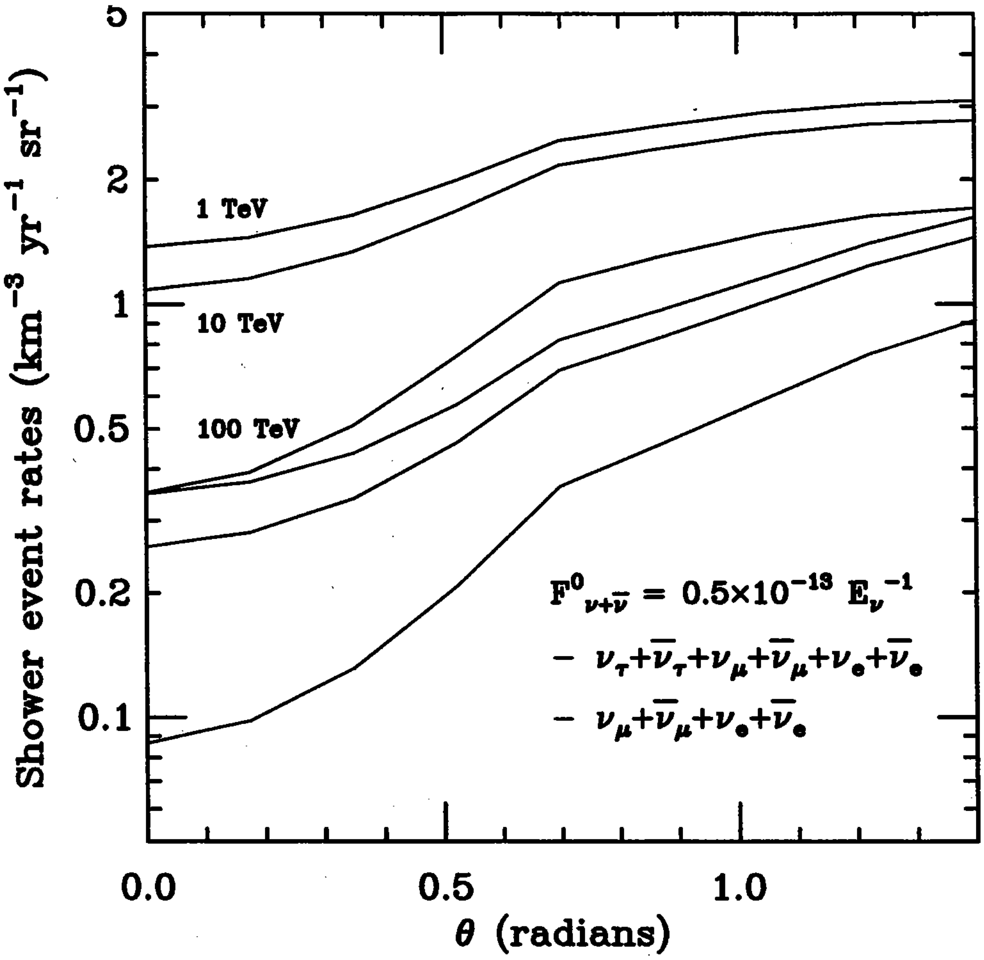
  AGN M95, $\mathbf{E^{-2}}$

- *Enhancement is less pronounced at smaller nadir angles and for increasing threshold of energy*

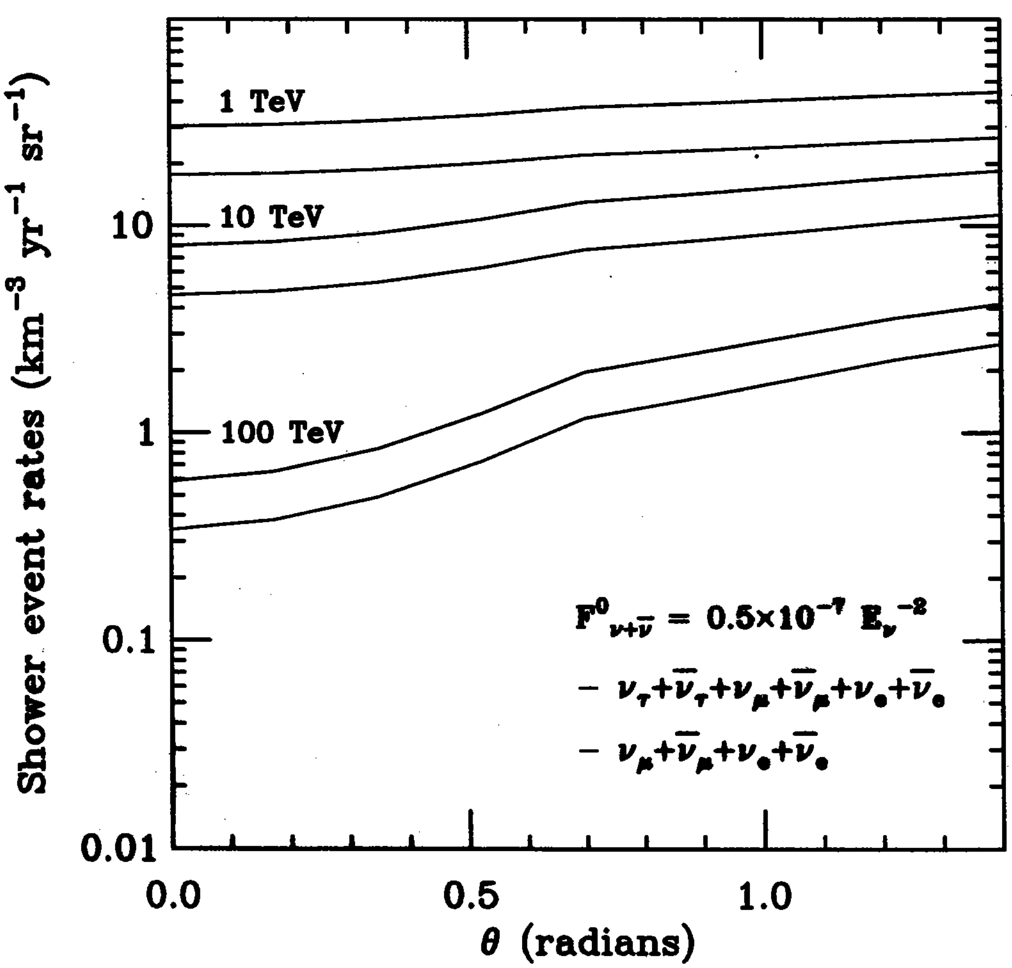
- *For flatter fluxes the enhancement is larger, up to a factor of 2*

  TD SLSC, $\mathbf{E^{-1}}$

- **Contributions from ν and $\bar{\nu}$**
- **Threshold energy > 1 TeV, 10 TeV, 100 TeV**
- **Atmospheric background negligible at 10 TeV, 100 TeV**



Shower event rates (km^{-3} yr^{-1} sr^{-1})
1 TeV
10 TeV
100 TeV
$F^0_{\nu+\bar{\nu}} = 0.5\times10^{-13}\ E_\nu^{-1}$
– $\nu_\tau+\bar{\nu}_\tau+\nu_\mu+\bar{\nu}_\mu+\nu_e+\bar{\nu}_e$
– $\nu_\mu+\bar{\nu}_\mu+\nu_e+\bar{\nu}_e$
θ (radians)



Shower event rates (km^{-3} yr^{-1} sr^{-1})
1 TeV
10 TeV
100 TeV
$F^0_{\nu+\bar{\nu}} = 0.5\times10^{-7}\ E_\nu^{-2}$
– $\nu_\tau+\bar{\nu}_\tau+\nu_\mu+\bar{\nu}_\mu+\nu_e+\bar{\nu}_e$
– $\nu_\mu+\bar{\nu}_\mu+\nu_e+\bar{\nu}_e$
θ (radians)

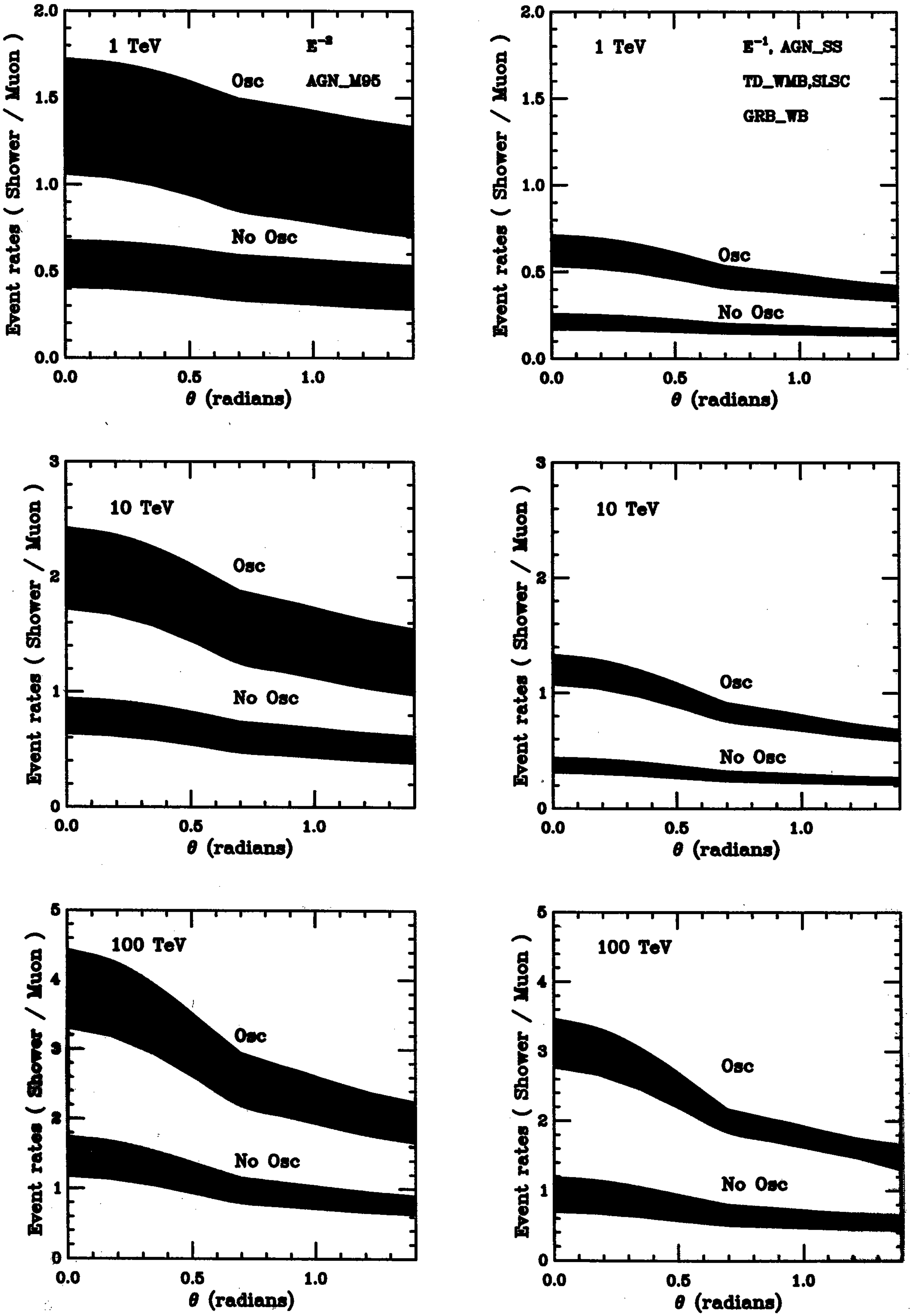
- *Enhancement: factor of 4 for flatter fluxes*

- *Ratio of the rates for oscillation and no oscillation scenarios:*

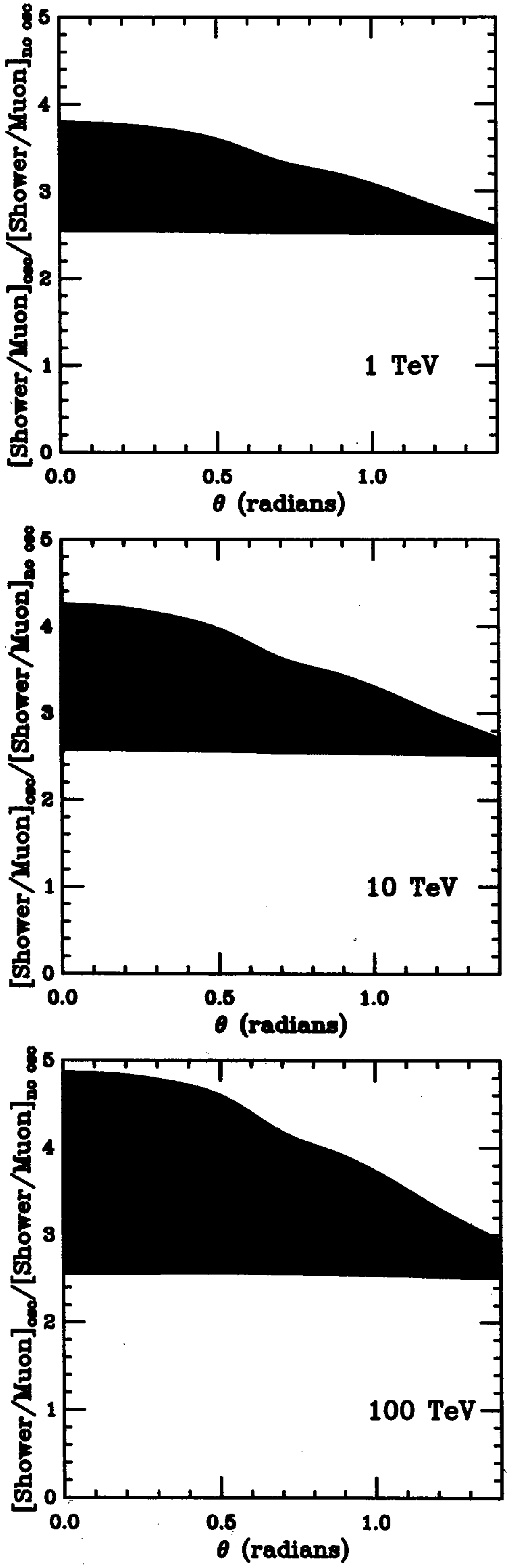
$$Ratio(R_1) = \frac{(\nu_\tau + \nu_\mu + \nu_e \to \mu)_{osc}}{(\nu_\mu + \nu_e \to \mu)_{noosc}} \sim 0.5$$

$$\boldsymbol{Ratio}(R_2) = \frac{(\nu_\tau + \nu_\mu + \nu_e \to shower)_{osc}}{(\nu_\mu + \nu_e \to shower)_{noosc}} \sim 4.0(E^{-1}) \leftrightarrow 1.5(E^{-2})$$

- *Ratio of the ratios, i.e* $(R) \equiv R_2/R_1 > 2.4$ *independent of the initial flux (i.e. model independent)*



1 TeV
E^-2
AGN_M95
Osc
No Osc
1 TeV
E^-1, AGN_SS
TD_WMB,SLSC
GRB_WB
Osc
No Osc
10 TeV
Osc
No Osc
10 TeV
Osc
No Osc
100 TeV
Osc
No Osc
100 TeV
Osc
No Osc
Event rates (Shower / Muon)
θ (radians)



[Shower/Muon]osc/[Shower/Muon]no osc
θ (radians)
1 TeV
10 TeV
100 TeV
0
1
2
3
4
5
0.0
0.5
1.0

- For energies above 10^6 GeV, of relevance to OWL/EUSO, RICE and ANITA, we need to include the energy loss of the τ propagating through the Earth.
- Energy loss processes for muons and taus:
  - ⋆ Bremsstrahlung
  - ⋆ Ionization
  - ⋆ Pair Production
  - ⋆ Photonuclear Processes

S.I. Dutta, M.H. Reno, I. Sarcevic and D. Seckel, PRD63, 094020 (2001).

S.I. Dutta, I. Mocioiu, J. Jones, M.H. Reno and I. Sarcevic, (2003).

- For energies above 10^6 GeV, new physics might become relevant, such as exchange of bulk gravitons (i.e. Kaluza-Klein modes) in the neutral-current interactions. (Fig)
- Possibility of testing theory of large extra dimensions with ultrahigh energy neutrinos?

S. Nussinov and R. Shrock, PRD59, 105002 (1999); PRD64, 47702 (20
P. Jain, D.W. Mc Kay, S. Panda and J. Ralston, PLB484, 267 (2000).
C. Tyler, A. Olinto and G. Sigl, PRD63, 055001 (2001).
H. Davoudiasi, J.L. Hewett and T.G. Rizzo, PLB549, 267 (2002).

Tau Energy Loss

- ⋆ *Tau Energy Loss Significant*
  $(E > 10^8 GeV)$

- ⋆ *Tau Decays Important*
  $(E < 10^8 GeV)$

- ⋆ *Average Tau Range for* $E > 10^9 GeV$

  (→ 17 Km in Water)
  (→ 4.7 Km in Iron)

Dutta, Reno, Sarcevic & I. S.
PR D63, 094020 (2001)

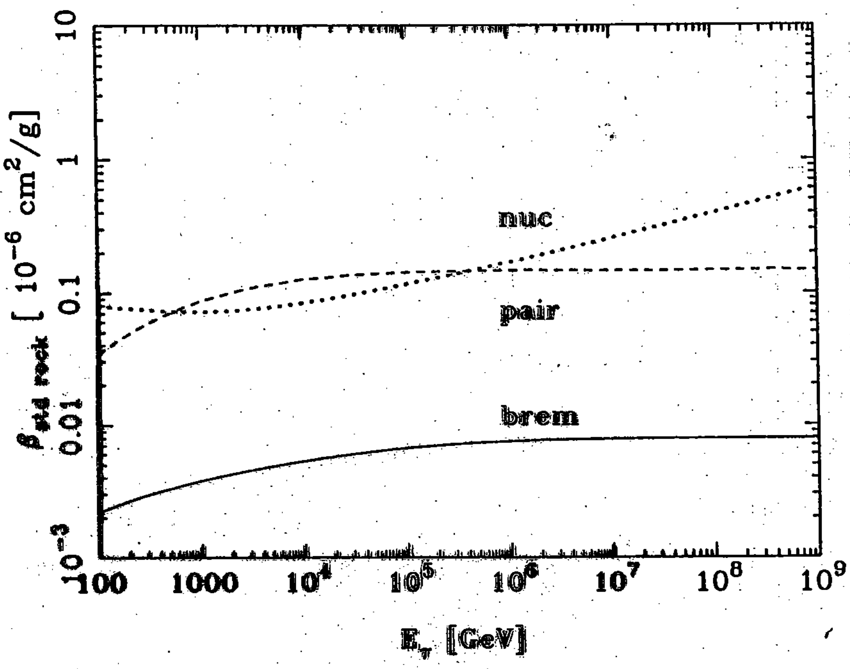
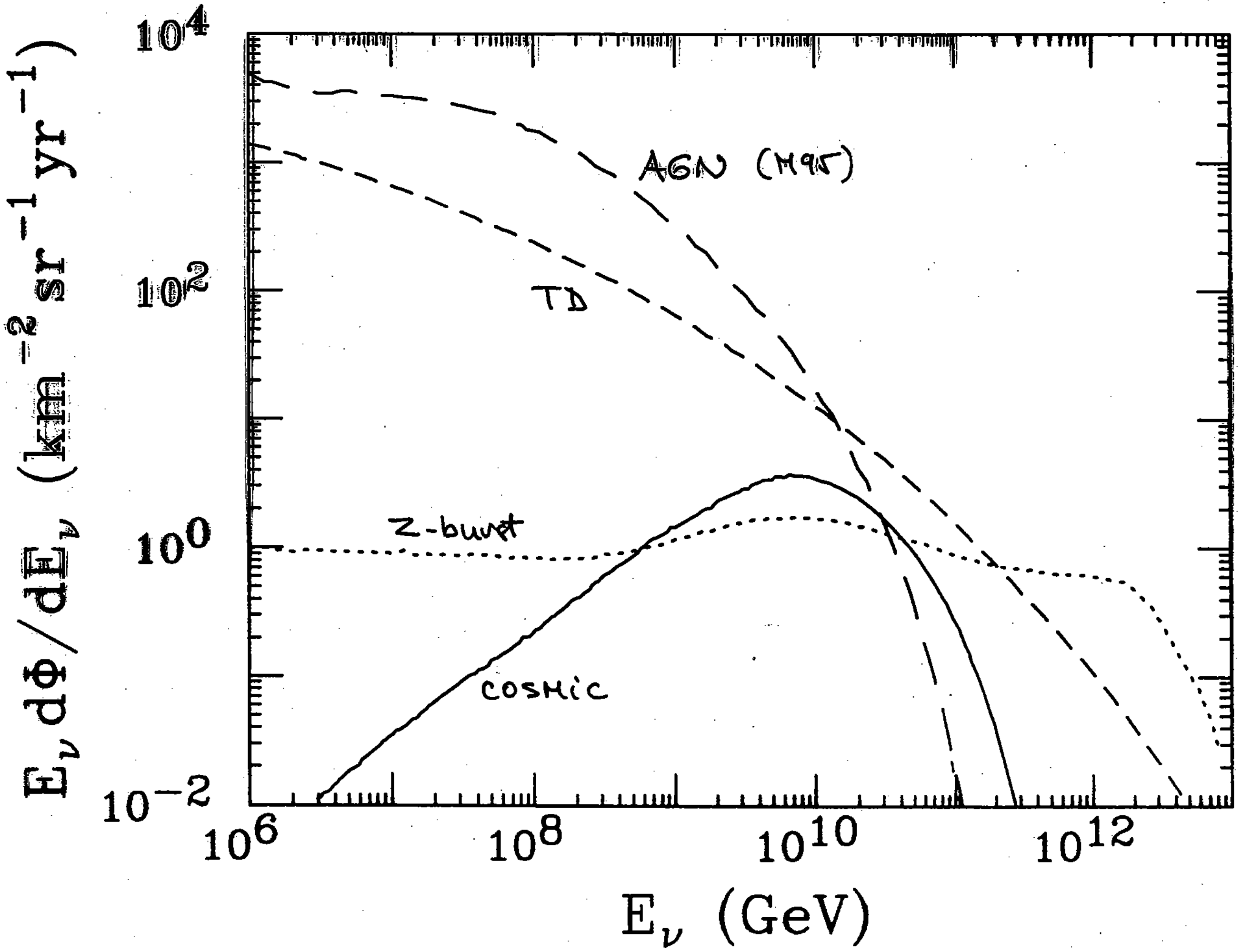


FIG. 6. The β value for tau in standard rock ($A = 22$), including bremsstrahlung (solid line), pair production (dashed) and photonuclear (ALLM) (dotted) interactions.



10^4
10^2
10^0
10^{-2}
10^6
10^8
10^{10}
10^{12}
$E_\nu d\Phi/dE_\nu$ $(km^{-2} sr^{-1} yr^{-1})$
E_ν (GeV)
AGN (M95)
TD
Z-burst
COSMIC

ANITA: Antarctic Impulsive Transient Antenna

JPL | UNIVERSITY OF HAWAII AT MANOA | UCI | UCLA | UNIVERSITY OF DELAWARE | PENNSTATE

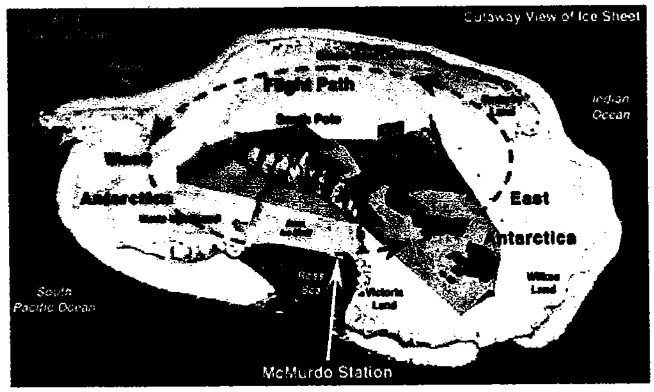
Scien[illegible] Detection of *ultra[illegible]mic neutrinos*

ANITA addresses NASA Structure and Evolution of the Universe (SEU) themes:

- Examines the *ultimate limits of energy in the universe* by measurements of completely new kinds of energetic particles: **neutrinos**, which are the only known ultra-high-energy particles that are able to reach earth unabsorbed from cosmological distances
- Probes the *nature and origin of the highest energy cosmic rays*, via the most sensitive observation to date of their characteristic neutrino by-products.

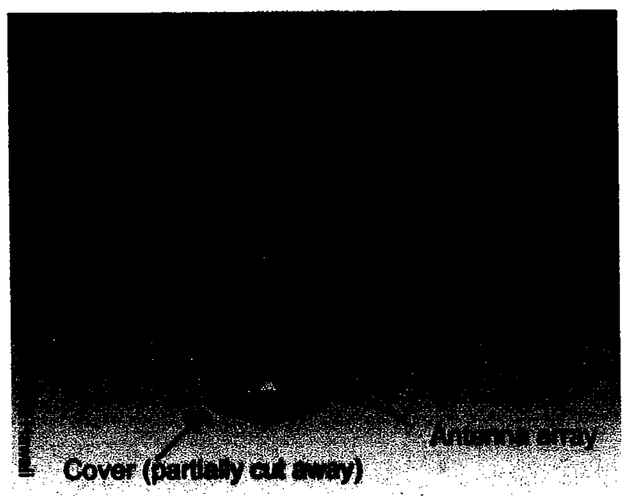
Mission Overview: *A long duration balloon mission over Antarctica*

- First flight in 2004-2005, two additional flights in 05-06, 06-07
- Each Flight: 9-12 days; Baseline Mission plan: 30 days total flight time
- Radio-frequency monitoring of Antarctic ice sheet from ~40 km altitude
- Flights are circumpolar due to continuous wind circulation around south pole
- Neutrino cascades within ice sheet produce strong Electro-magnetic pulse (EMP) which propagates through ice
- Antarctic ice is transparent to radio waves up to ~1-1.5 GHz
- Ice sheet becomes a neutrino "converter:" neutrinos enter and radio waves come out.
- Effective telescope area: ~1M km^2!



A cutaway view of Antarctic ice sheet: ANITA observations penetrate deep into the ice itself. Balloon flight path is shown.

Science Payload: [illegible] *Dual-Polarized Antennas cov[illegible] 1.5 GHz*



- Array of low-gain log-periodic antennas views ice sheet out to ~680 km
- Utilize Askaryan effect in neutrino cascades: radio pulse mechanism tested at accelerators
- ~10° azimuth resolution via antenna beam gradiometry within antenna clusters
- ~3° elevation resolution by interferometry between top & bottom antenna clusters
- Pulse polarimetry to get additional information on neutrino direction

1 SCIENCE INVESTIGATION

1.1 SCIENTIFIC GOALS AND OBJECTIVES

The primary objectives of the Antarctic Impulsive Transient Antenna (ANITA) mission are to extend the reach of NASA observatories into the realm of high energy neutrino astronomy, and thereby to investigate and constrain the nature of the sources of the highest energy cosmic ray particles, by direct detection and characterization of the neutrinos that are predicted to be strongly correlated to them [1]. ANITA's results will add significantly to our fundamental knowledge in two of NASA's Structure and Evolution of the Universe (SEU) Primary Science Themes:

- Examining the ultimate limits of gravity and energy in the universe, and
- Identifying the origin of the high energy cosmic rays.

The observation over the last 40 years of several dozen cosmic ray events with single-particle energies of up to 50 Joules (equivalent to a major-league fastball) poses among the most intriguing and intractable problems in high energy astrophysics. No known process can give rise to particles of energies a billion times higher than those produced in man-made accelerators, as these have. Stated simply, these particles should not exist. Yet in fact they do exist and continue to be observed with regularity every year. If they arise from sources at cosmological distances (for example, from unknown processes in gamma- ray bursts) then they should not be able to propagate to earth without being utterly absorbed. Yet if they arise from sources near enough to avoid absorption, we are at a loss to identify their sources.

Observation of high energy neutrinos are one of the crucial keys to unlock this mystery. If, on the one hand, the sources are at cosmological distances, then there is a corresponding and closely-coupled flux of neutrinos that result from the summed interactions of these cosmic rays throughout the universe. This process occurs at an absorption edge known as the Greisen-Zatsepin-Kuzmin (GZK) cutoff, postulated first in the early 1960's [7, 8].

If, on the other hand, these particles arise from sources local to our galaxy or the Local Group of galaxies, then high-energy neutrinos are still the most likely and compelling signature of the potentially exotic processes by which these local interactions [10, 14, 13]. Under almost any conceivable theory, the observation of associated high energy neutrinos (or even significant limits to their flux) provides necessary and in many cases sufficient evidence to decide between the competing models. ANITA will provide the very first opportunity to view the landscape of the ultra-high energy universe, unaffected by absorption, for neutrinos propagate freely to earth even from cosmological distances.

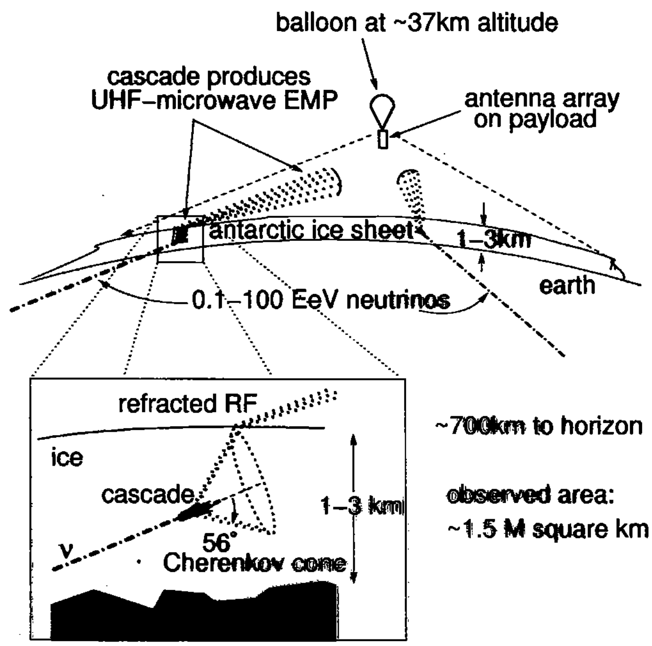


Figure 1: *Schematic of the ANITA concept.*

1.1.1 VALUE TO PRIMARY NASA SCIENCE THEMES.

1.1.1.1 SEU Fundamental Scientific Quest: *Examining the Ultimate limits of gravity and energy in the universe.*

ANITA, as an Antarctic long-duration balloon flight, will synoptically observe the Antarctic ice sheet out to a horizon approaching 700 km, giving a detection volume of order 1M km^3. ANITA will search for radio pulses that arise from electromagnetic cascade interactions of the high energy neutrinos within the ice. Such radio pulses, recently confirmed in accelerator experiments, easily propagate through the ice due to its remarkable radio transparency. Fig. 1 gives a schematic view of the concept of ANITA, indicating the basic geometry for the coherent Cherenkov radio pulse produced by the cascades in Antarctic ice, and the synoptic view of the balloon payload.

ANITA measurements are directly sensitive to established but untested models for many different kinds of high energy particle astrophysics phenomena in addition to the GZK process, since high energy neutrinos are intimately coupled with all aspects of energetic hadron interactions and acceleration. ANITA will act as a pathfinding mission for high energy neutrino astronomy, because it will achieve extremely high sensitivity in a relatively short timeframe. The mission will provide an early view of the potential neutrino fluxes from many possible sources. Because neutrinos can escape freely from sources in which all other forms of radiation can be heavily absorbed, ANITA will be sensitive to energy from astrophysical objects that may not be observable in any other way.

1.1.1.2 SEU Focused Research Campaign Topic: *Identifying the origin of the high energy cosmic rays.*

ANITA will be uniquely sensitive to the GZK neutrinos that are produced by the integrated interactions of the highest energy cosmic rays throughout the universe. Fig. 2 shows a plot of various neutrino models, limits, and the estimated sensitivity of ANITA for the baseline 30-day Antarctic exposure (3 flights) and for the maximal 100 days that could be achieved when the Ultra-long duration balloon (ULDB) flights become available. Even a single 10-day flight for ANITA is capable of beginning to constrain the GZK neutrino energy spectrum. Given the high difficulty and cost of instrumenting even a small fraction of the effective observed fiducial volume that ANITA can monitor, our proposed mission, at just under \$23M, is a fraction of the cost of large ground-based neutrino observatories now planned. ANITA is an extremely cost effective approach toward a difficult but scientifically compelling problem.

As a pathfinding mission with high sensitivity but only modest resolution and precision, ANITA will by no means displace the need for more precise tracking detectors once the fluxes are established. Rather, it enables careful and informed design of future detectors which will help to optimize their use of costly resources and ultimately enhance their science return for a relatively modest early investment.

1.1.2 Relation to Past, Current, and Future Investigations and Missions.

There are no current or past NASA missions that have directly addressed either neutrino astronomy or the problem of the highest energy cosmic rays. To date all NASA missions that have measured cosmic rays have done so at energies below 1 PeV, several orders of magnitude below the energy regime that ANITA will explore. There are several ground-based efforts now currently addressing the problem of high energy neutrino astronomy, to be discussed in a later section.

ANITA has direct relevance to one mission

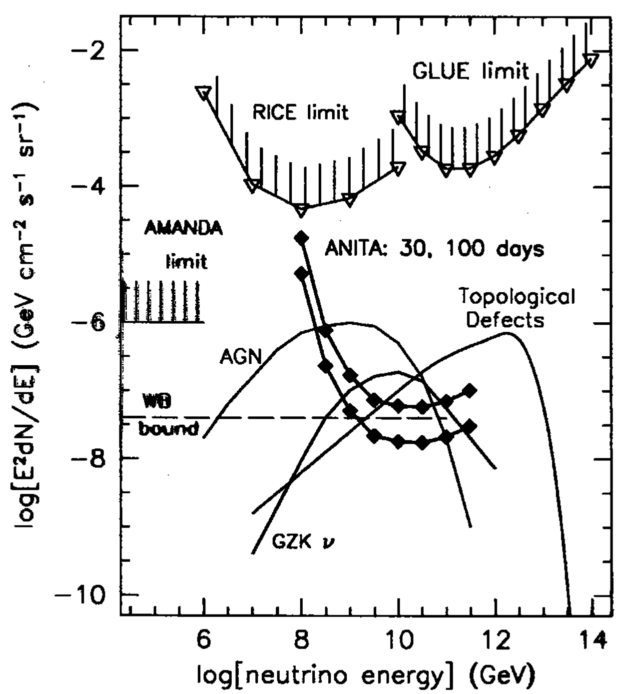
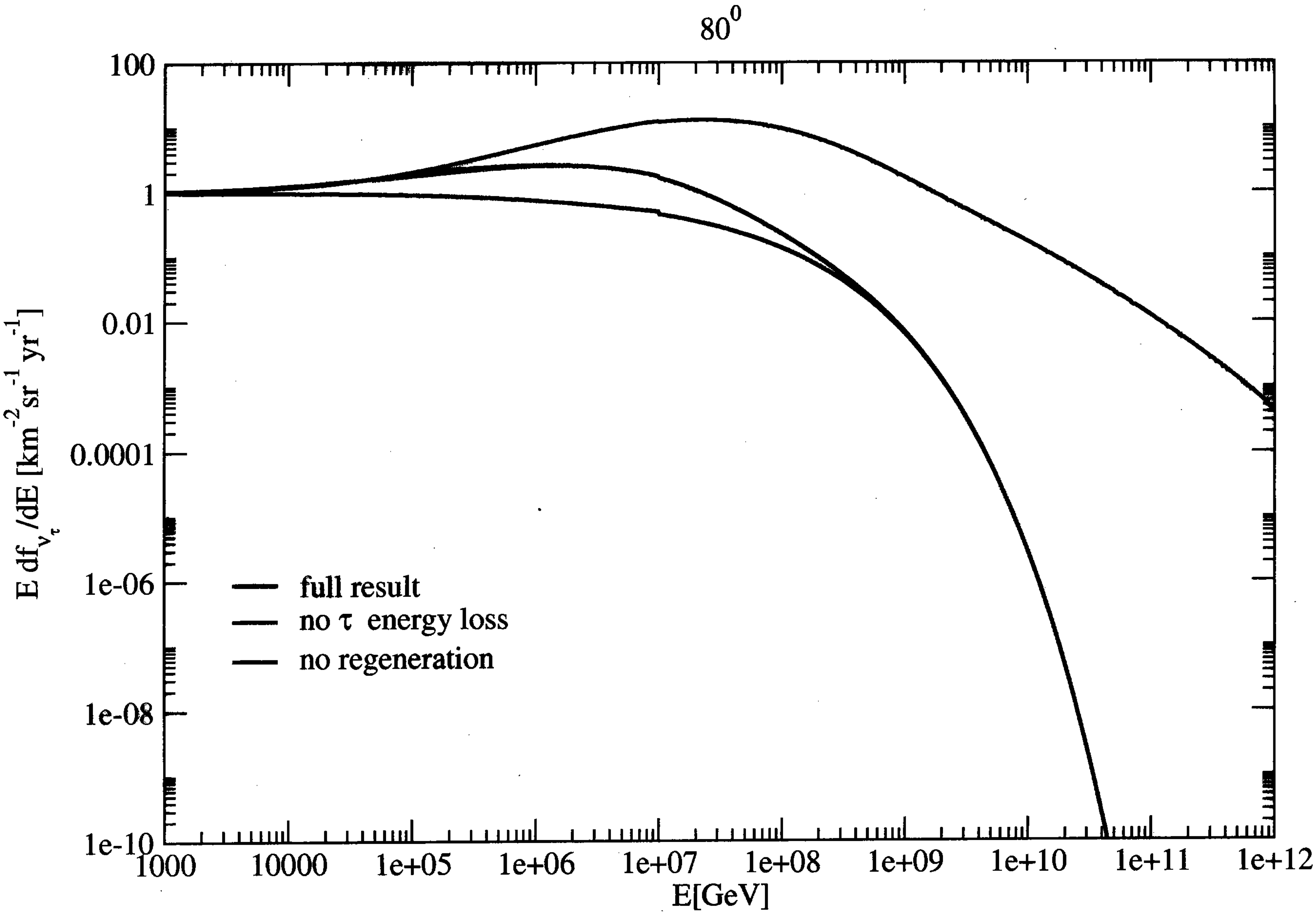


Figure 2: *Various representative neutrino models and limits are shown along with estimated sensitivity of ANITA for the 30 day mission goal and extended mission 100 day flight time, assuming 75% observing efficiency. The AGN model is from Mannheim[9]. The Waxman/Bahcall bound[11] applies to optically thin sources. Topological defect model is from Protheroe & Stanev [12].*



80^0
100
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1e+08
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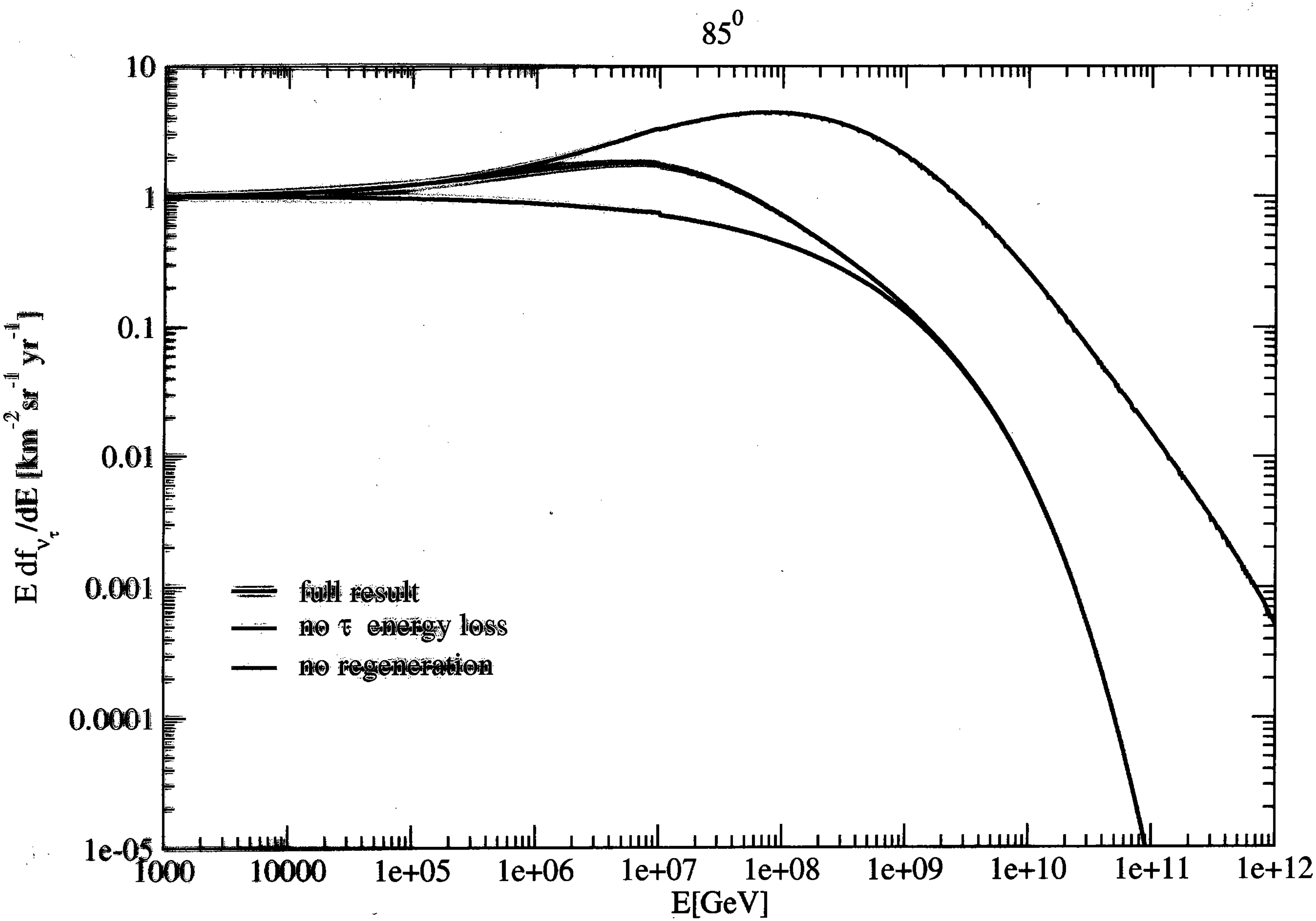
E[GeV]
E df$_{\nu_\tau}$/dE [km^{-2}sr^{-1} yr^{-1}]
full result
no τ energy loss
no regeneration



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E[GeV]
full result
no τ energy loss
no regeneration
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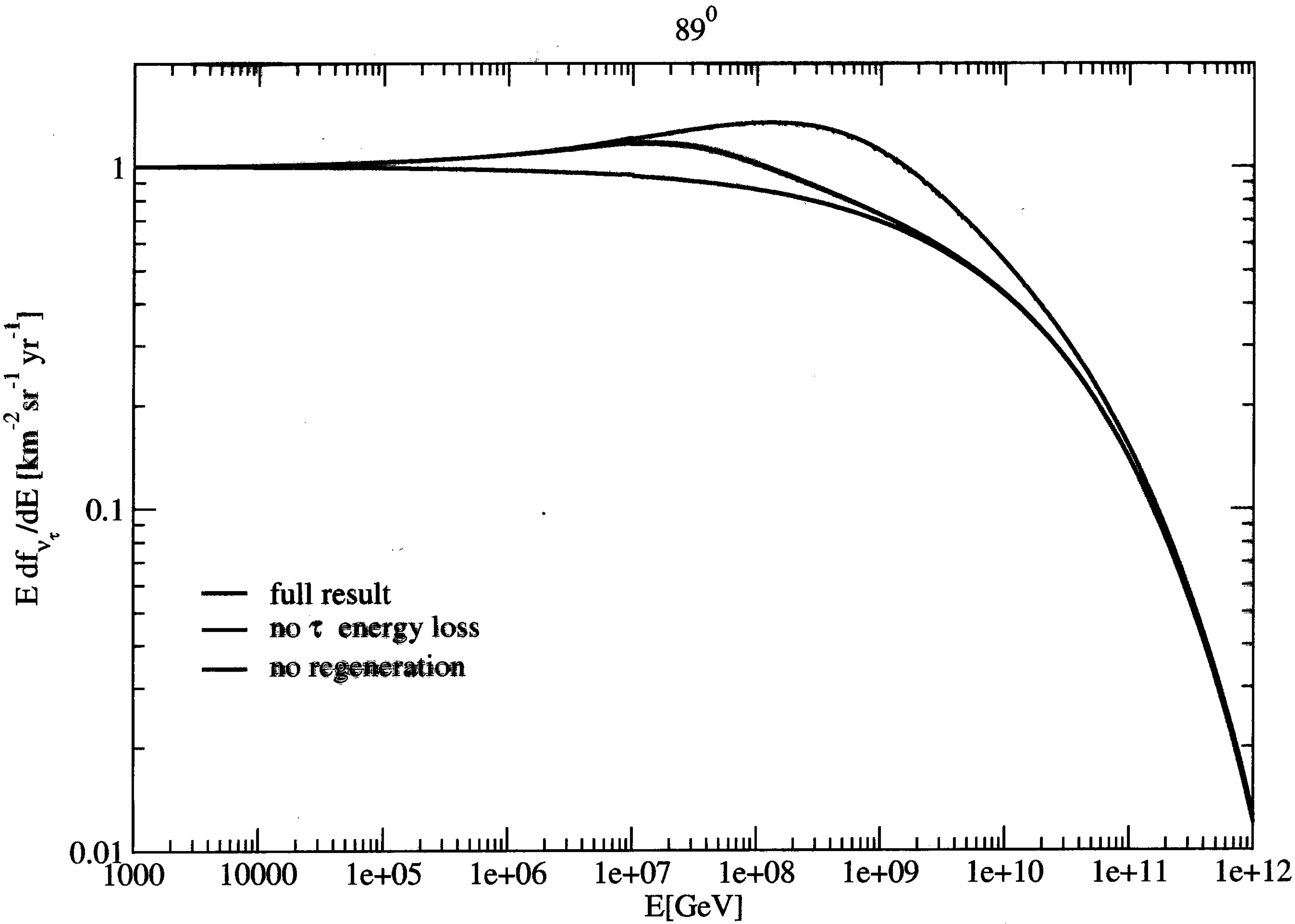
1e+11
1e+12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E df_{ν_τ}/dE [km^{-2}sr^{-1} yr^{-1}]
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0.01
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1e+06
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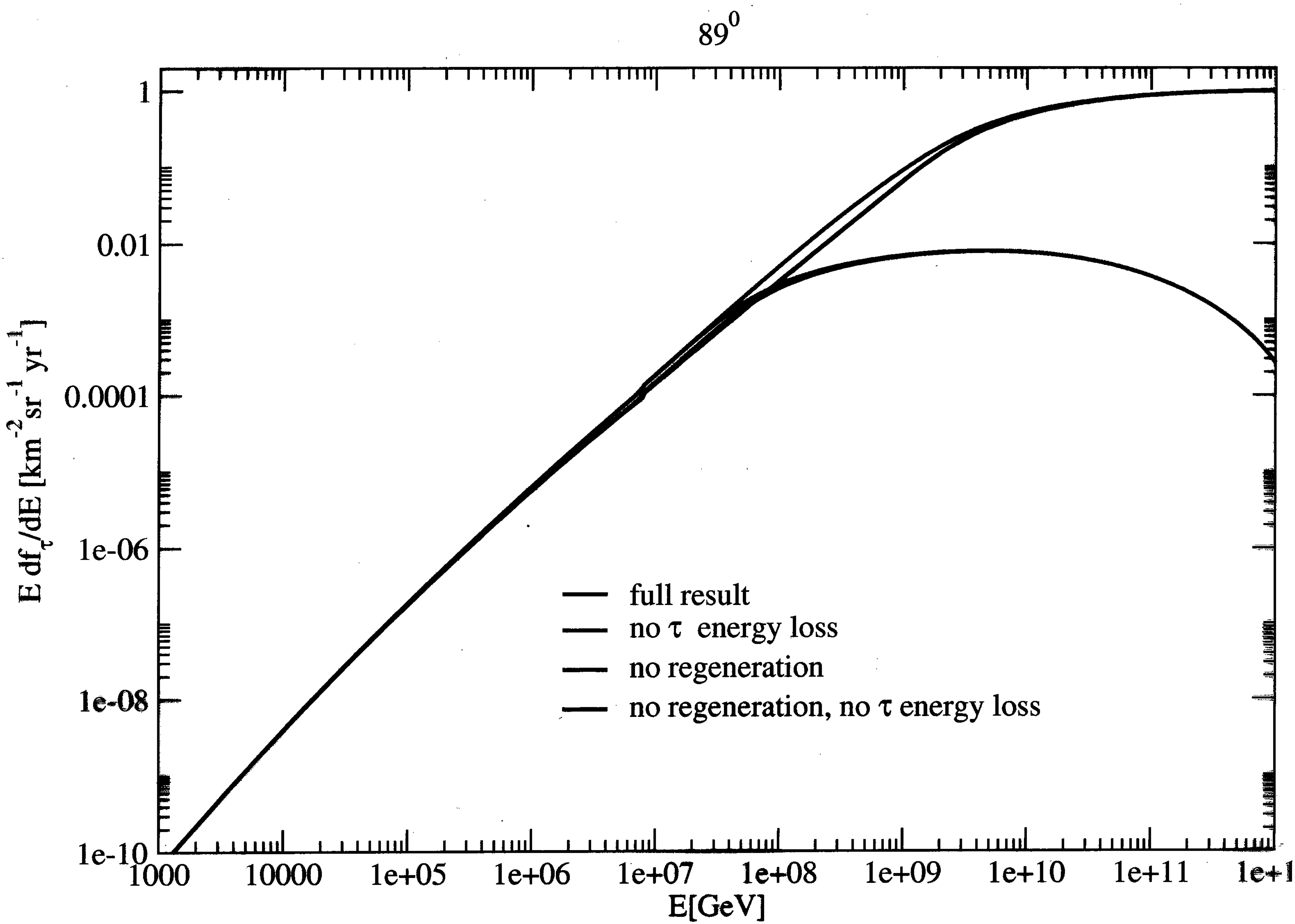
1e+08
1e+09
1e+10
1e+11
1e+12
E[GeV]
full result
no τ energy loss
no regeneration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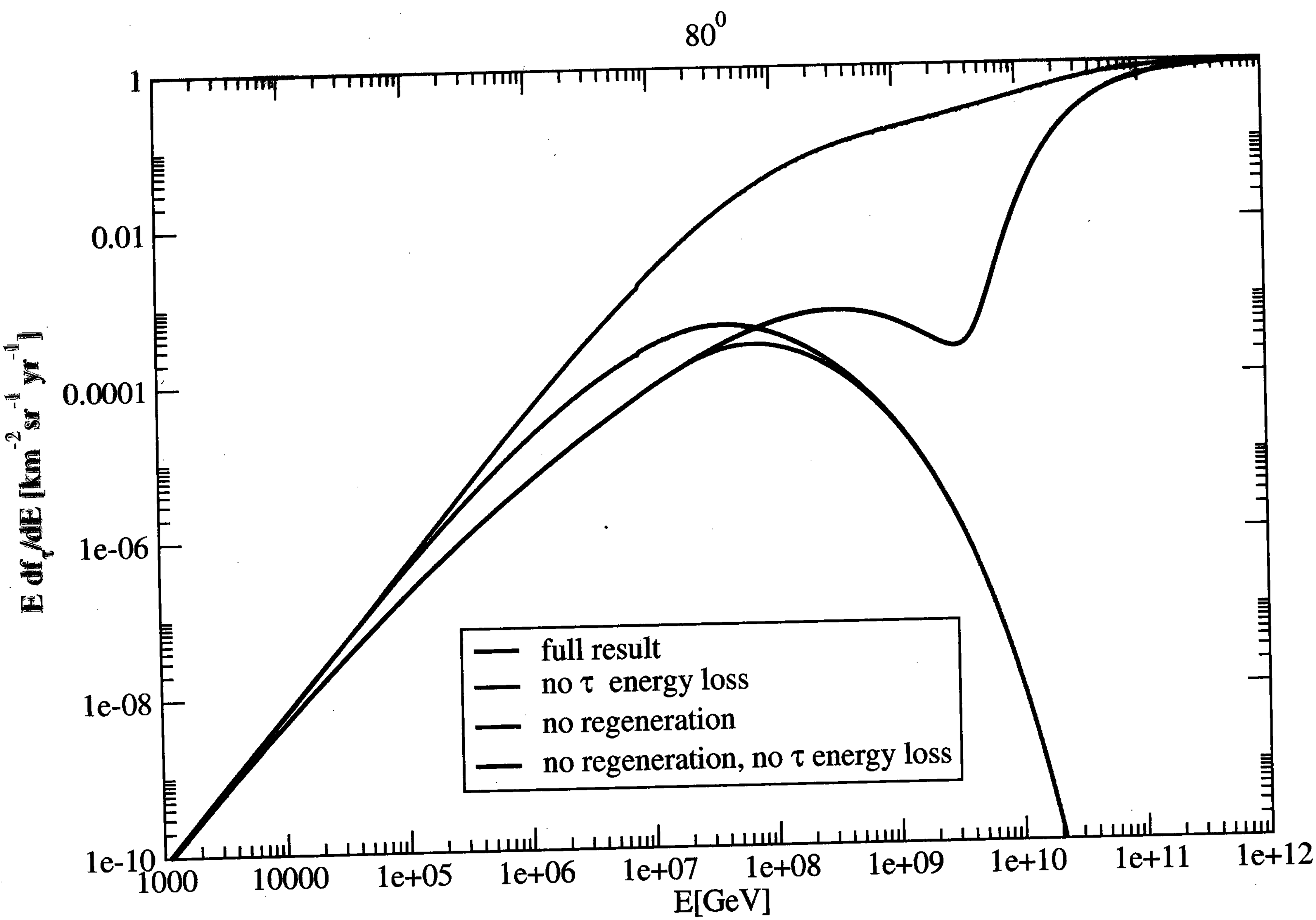
1e+09
1e+10
1e+11
1e+1
E[GeV]
E df$_\tau$/dE [km^{-2}sr^{-1} yr^{-1}]
full result
no τ energy loss
no regeneration
no regeneration, no τ energy loss



80^0
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10000
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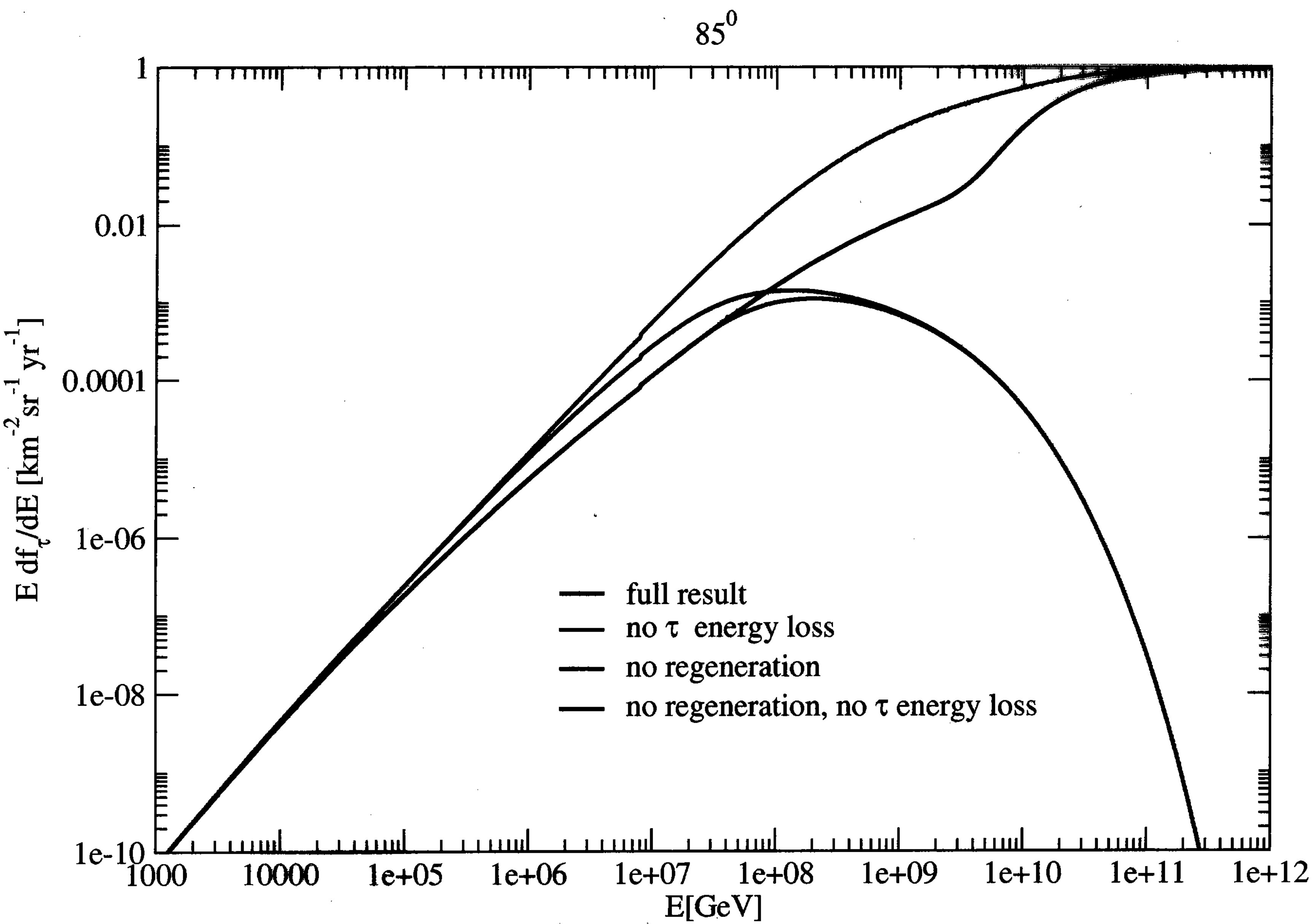
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E[GeV]
E df_τ/dE [km^-2 sr^-1 yr^-1]
full result
no τ energy loss
no regeneration
no regeneration, no τ energy loss



85^0
E df$_\tau$/dE [km^{-2}sr^{-1}yr^{-1}]
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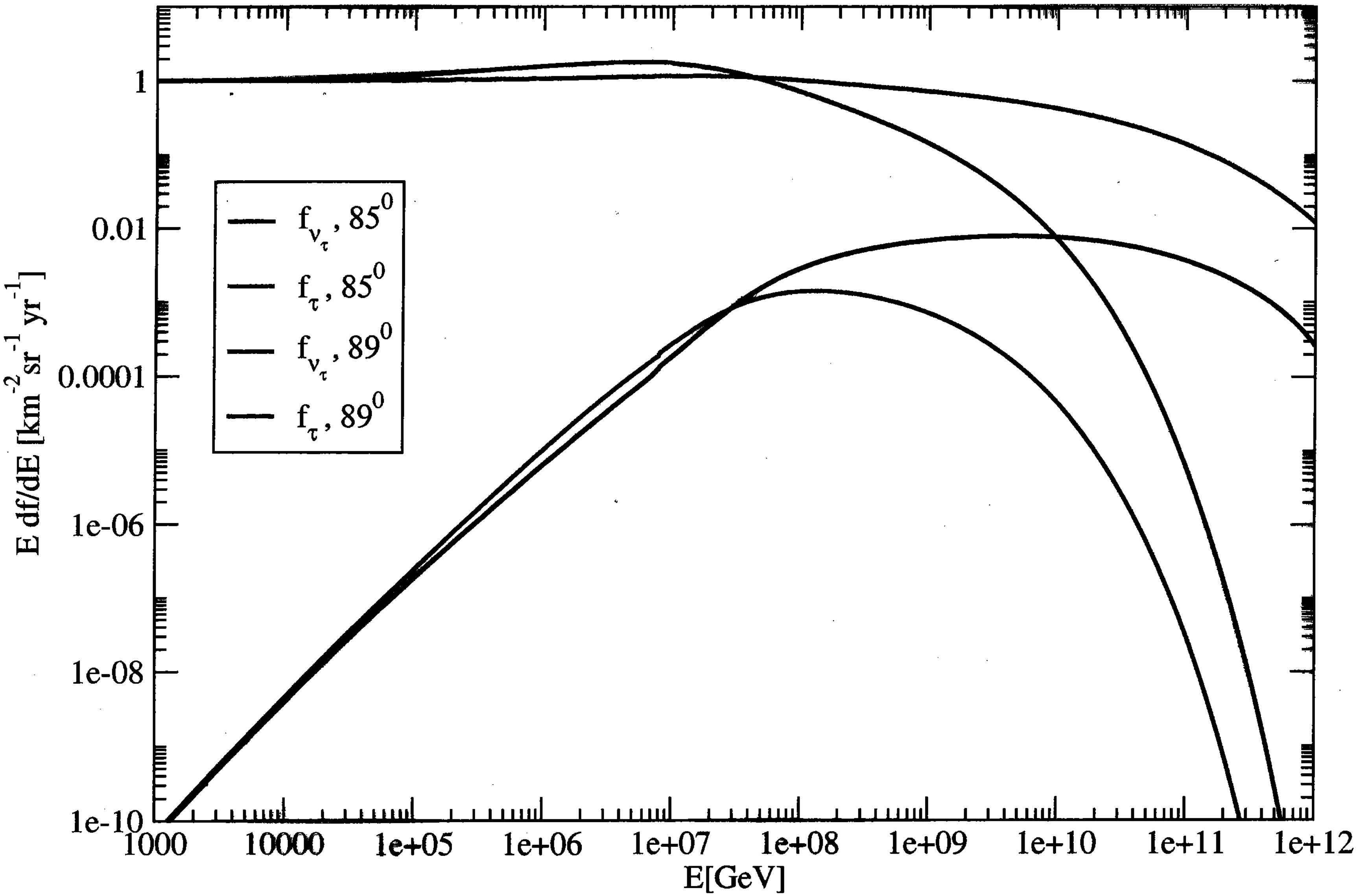
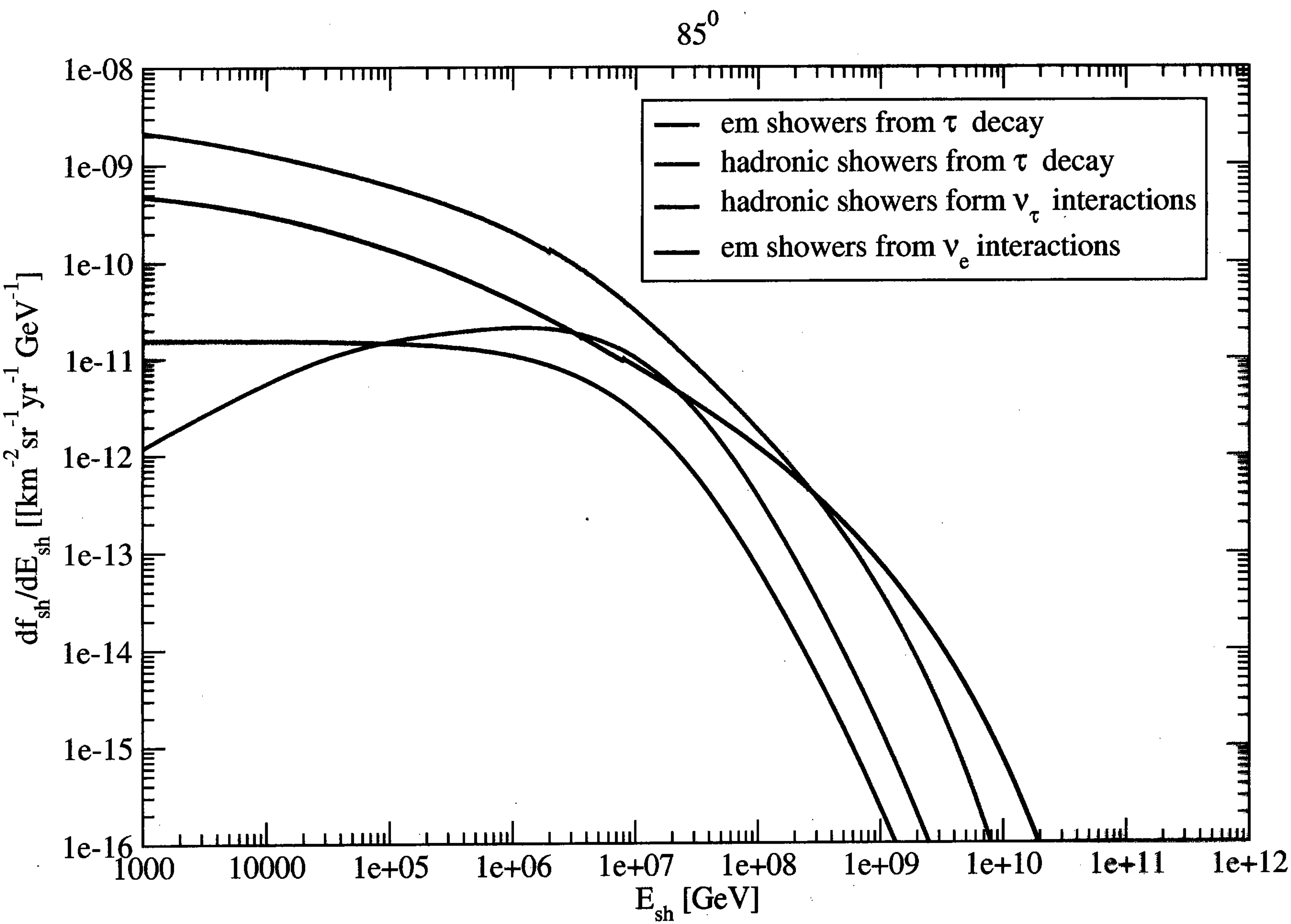
0.01
0.0001
1e-06
1e-08
1e-10
1000
10000
1e+05
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E[GeV]
full result
no τ energy loss
no regeneration
no regeneration, no τ energy loss



f_{ν_τ}, 85^0
f_τ, 85^0
f_{ν_τ}, 89^0
f_τ, 89^0
E df/dE [$km^{-2} sr^{-1} yr^{-1}$]
1
0.01
0.0001
1e-06
1e-08
1e-10
1000
10000
1e+05
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E[GeV]



85⁰
em showers from τ decay
hadronic showers from τ decay
hadronic showers form ν_τ interactions
em showers from ν_e interactions
df_sh/dE_sh [[km^-2 sr^-1 yr^-1 GeV^-1]
E_sh [GeV]
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
1e-14
1e-15
1e-16
1000
10000
1e+05
1e+06
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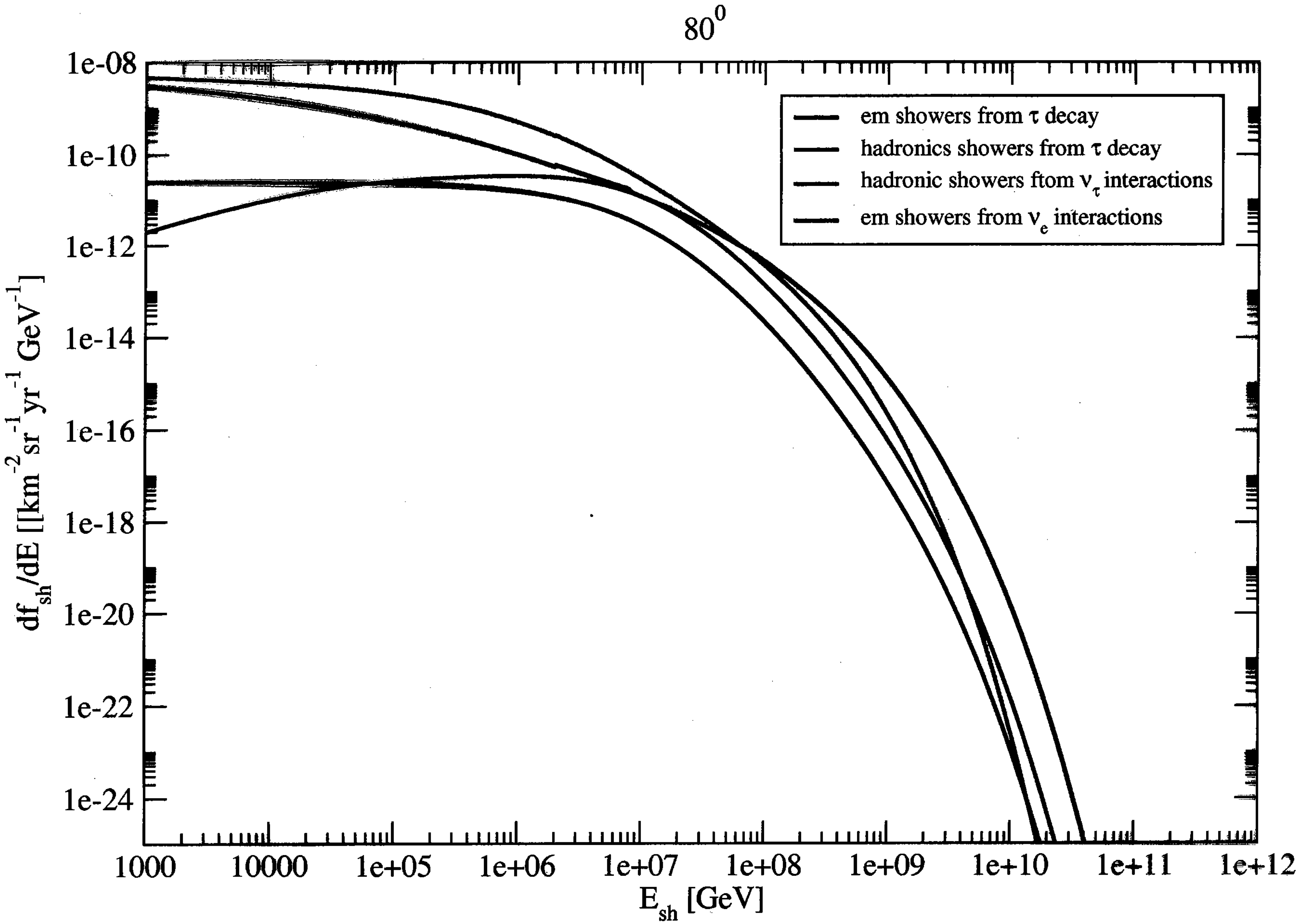
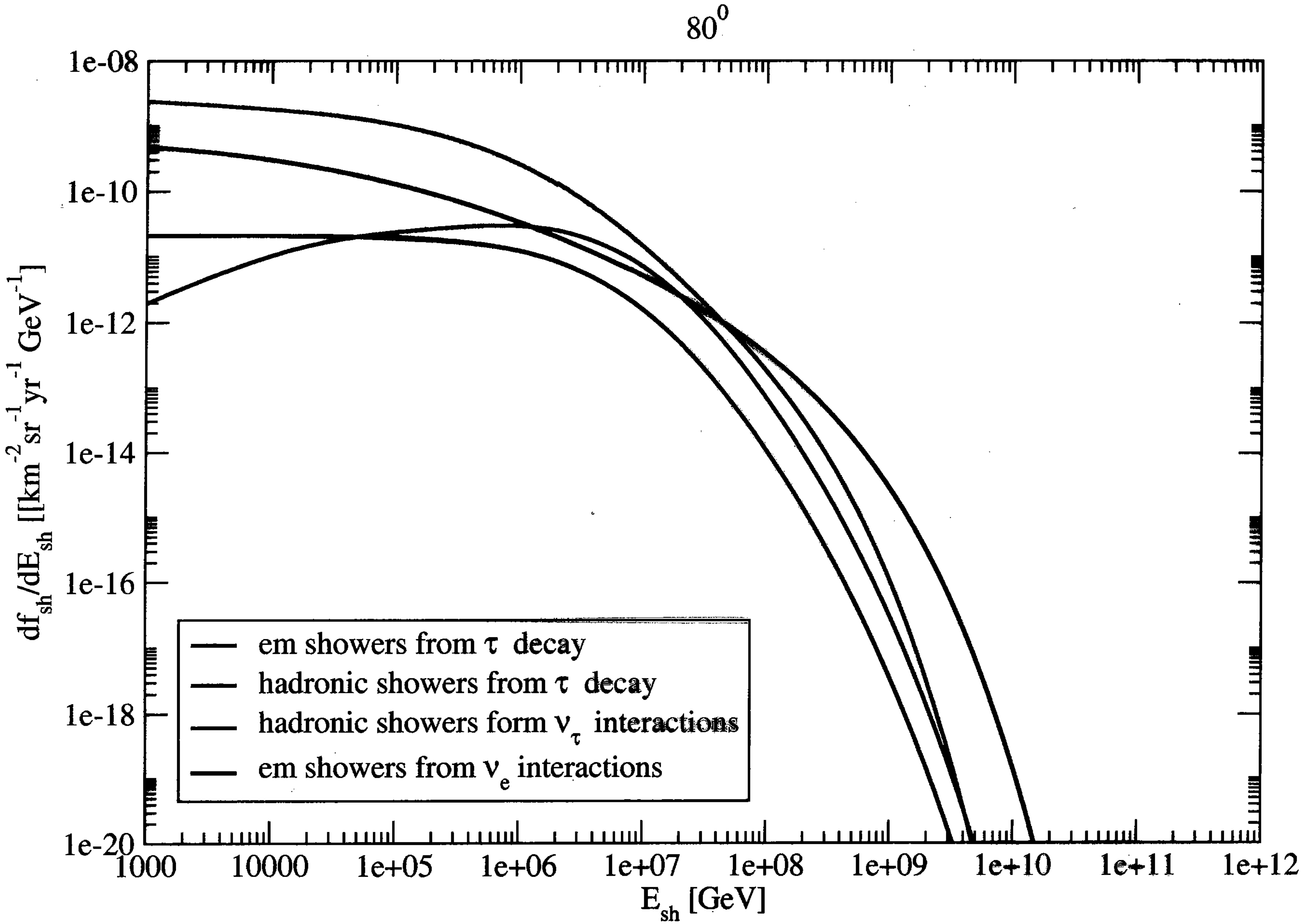
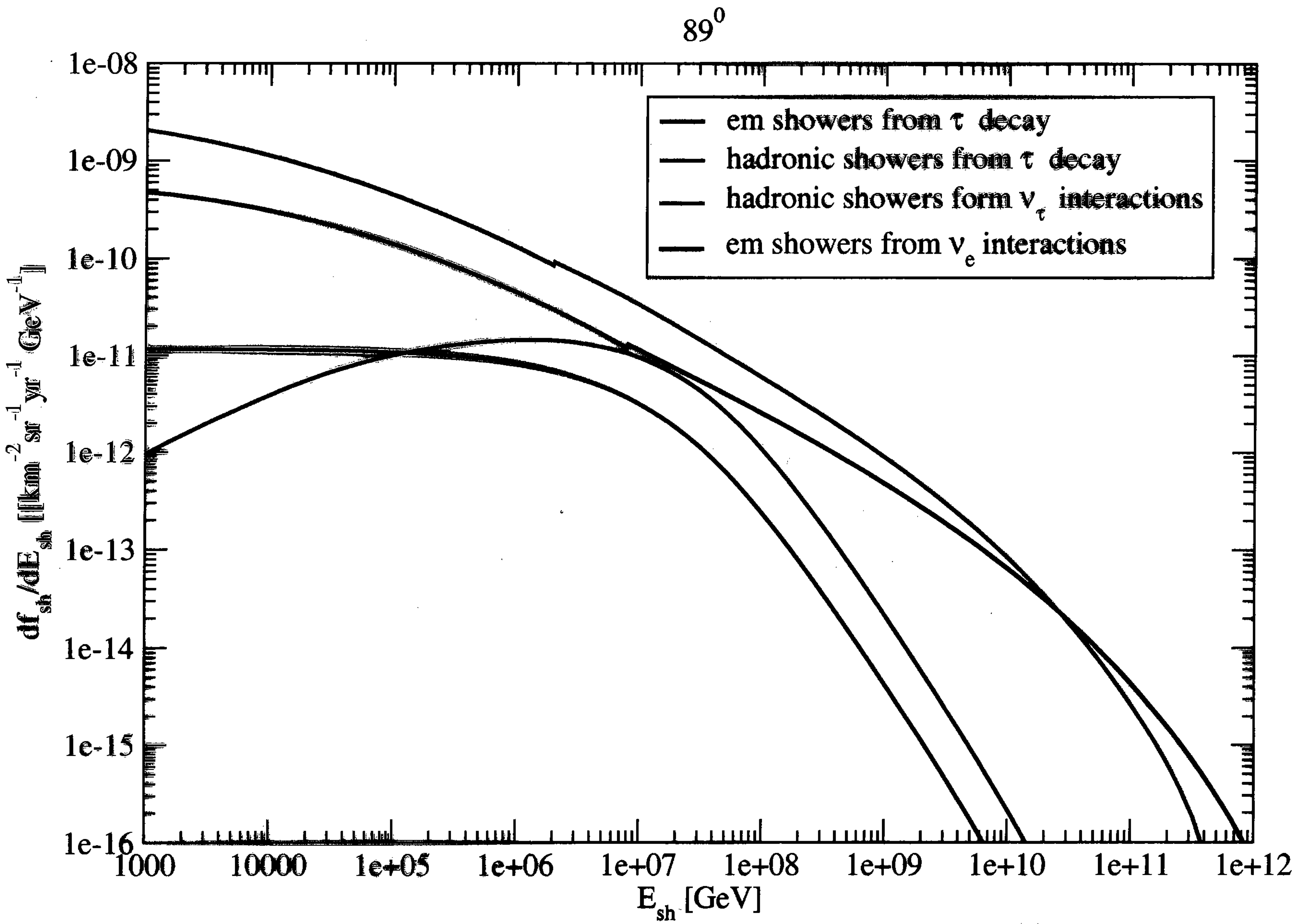
1e+08
1e+09
1e+10
1e+11
1e+12



80⁰
em showers from τ decay
hadronics showers from τ decay
hadronic showers ftom ν_τ interactions
em showers from ν_e interactions
1e-08
1e-10
1e-12
1e-14
1e-16
1e-18
1e-20
1e-22
1e-24
1000
10000
1e+05
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E_sh [GeV]
df_sh/dE [[km^-2 sr^-1 yr^-1 GeV^-1]

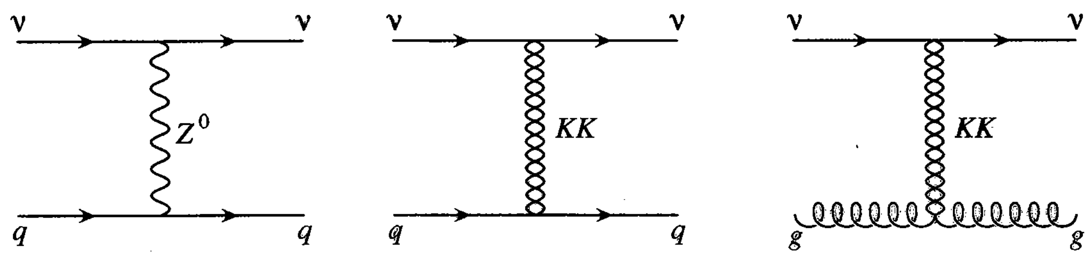


80°
1e-08
1e-10
1e-12
1e-14
1e-16
1e-18
1e-20
1000
10000
1e+05
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E_{sh} [GeV]
df_{sh}/dE_{sh} [[km^{-2}sr^{-1}yr^{-1} GeV^{-1}]
em showers from τ decay
hadronic showers from τ decay
hadronic showers form ν_τ interactions
em showers from ν_e interactions


89⁰
em showers from τ decay
hadronic showers from τ decay
hadronic showers form ν_τ interactions
em showers from ν_e interactions
df_sh/dE_sh [[km^-2 sr^-1 yr^-1 GeV^-1]]
E_sh [GeV]
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
1e-14
1e-15
1e-16
1000
10000
1e+05
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12

Strong Neutrino-Nucleon Interactions at Ultrahigh Energies?

In models based on extra dimensions neutrinos interact with quarks and gluons inside the nucleons via exchange of gravitons:

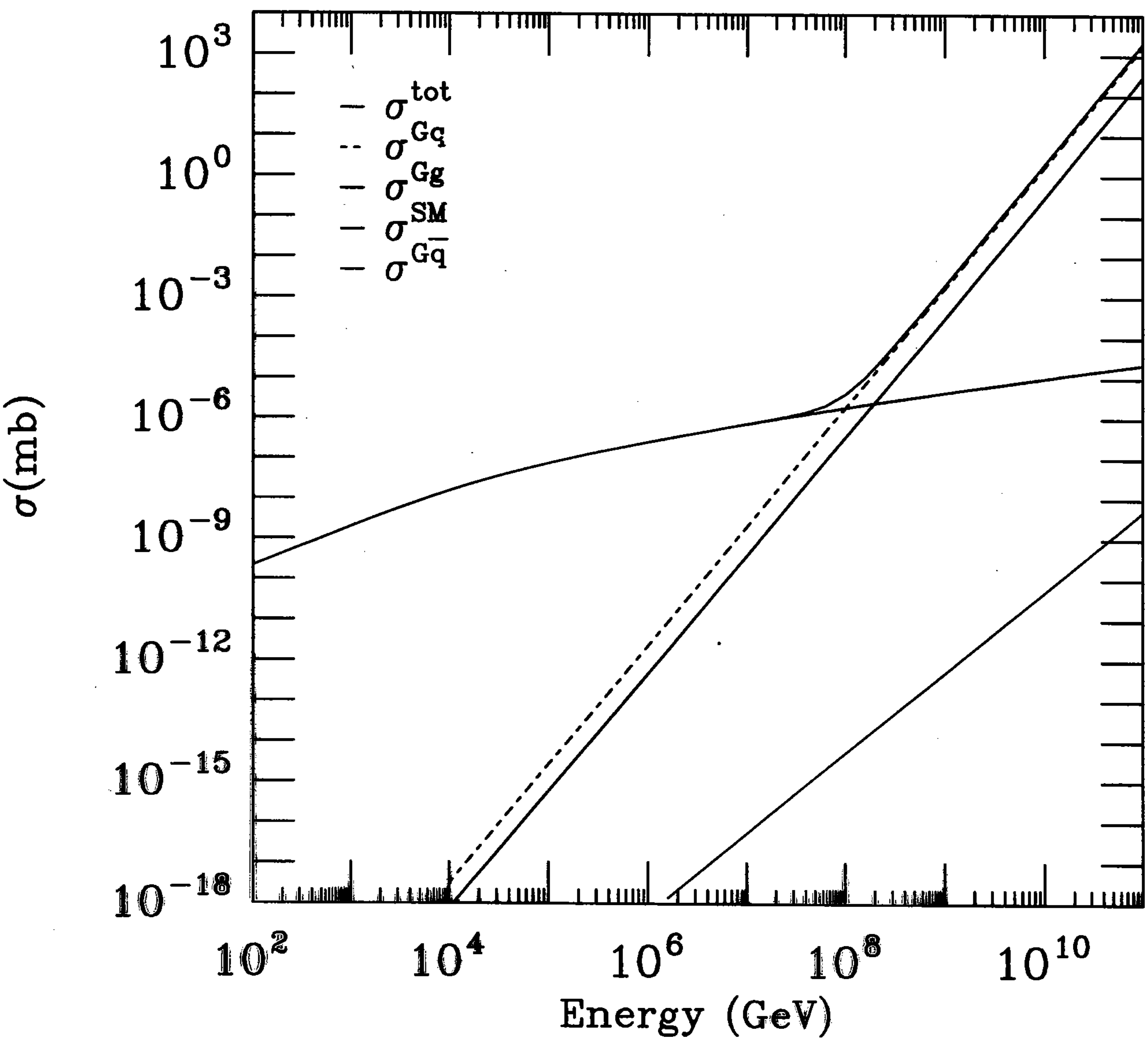


⋆ Neutral current cross section in the Standar Model is modified due to contributions of massive spin-2 states:

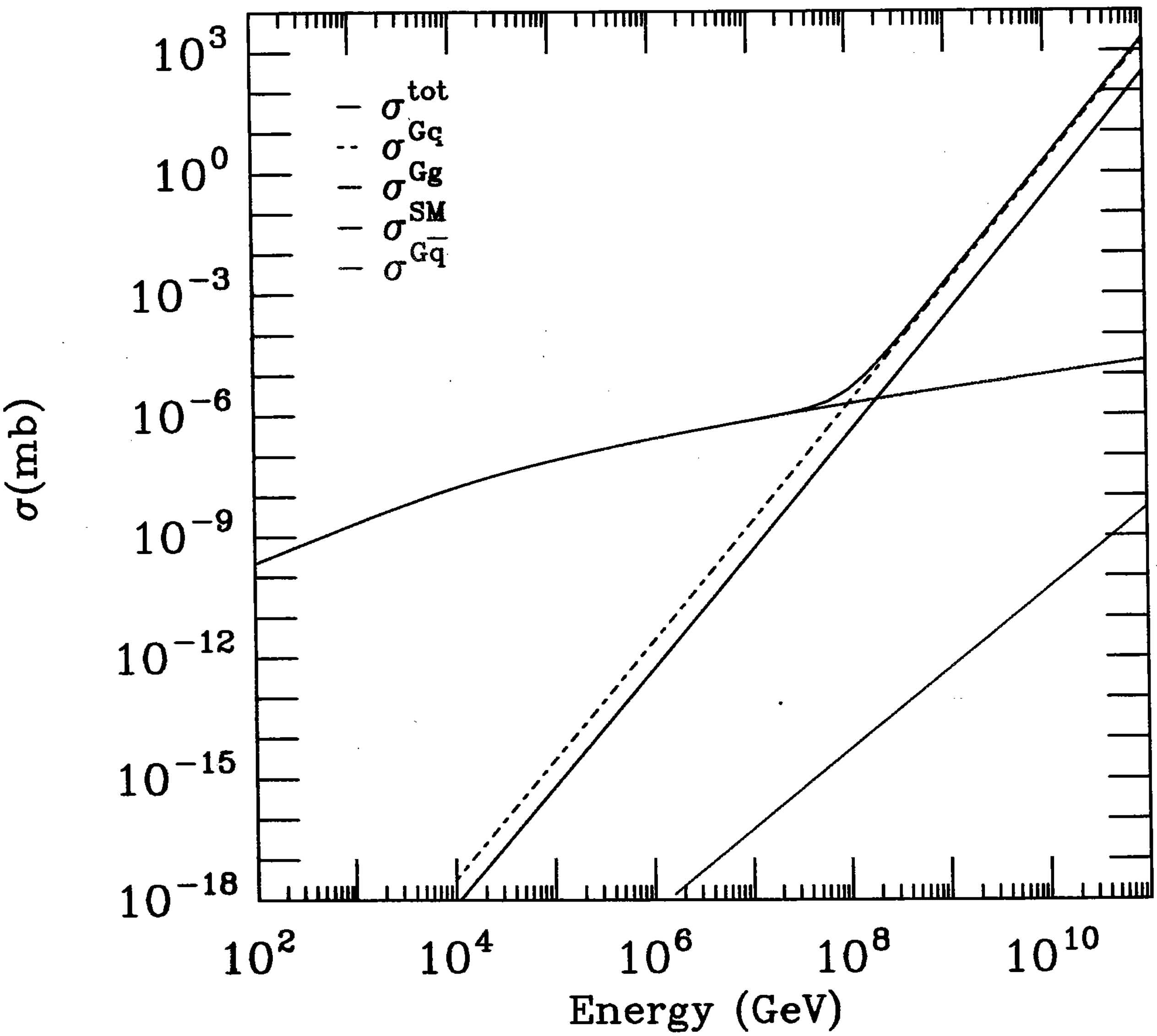
$$\frac{d\hat{\sigma}^{Gq}}{d\hat{t}} = \frac{\pi}{32M_s^8}\frac{1}{\hat{s}^2}\left[32\hat{u}^4 + 64\hat{u}^3\hat{t} + 42\hat{u}^2\hat{t}^2 + 10\hat{u}\hat{t}^3 + \hat{t}^4\right]$$

$$\frac{d\hat{\sigma}^{Gg}}{d\hat{t}} = \frac{\pi}{2M_s^8}\frac{\hat{u}}{\hat{s}^2}\left[2\hat{u}^3 + 4\hat{u}^2\hat{t} + 3\hat{u}\hat{t}^2 + \hat{t}^3\right]$$

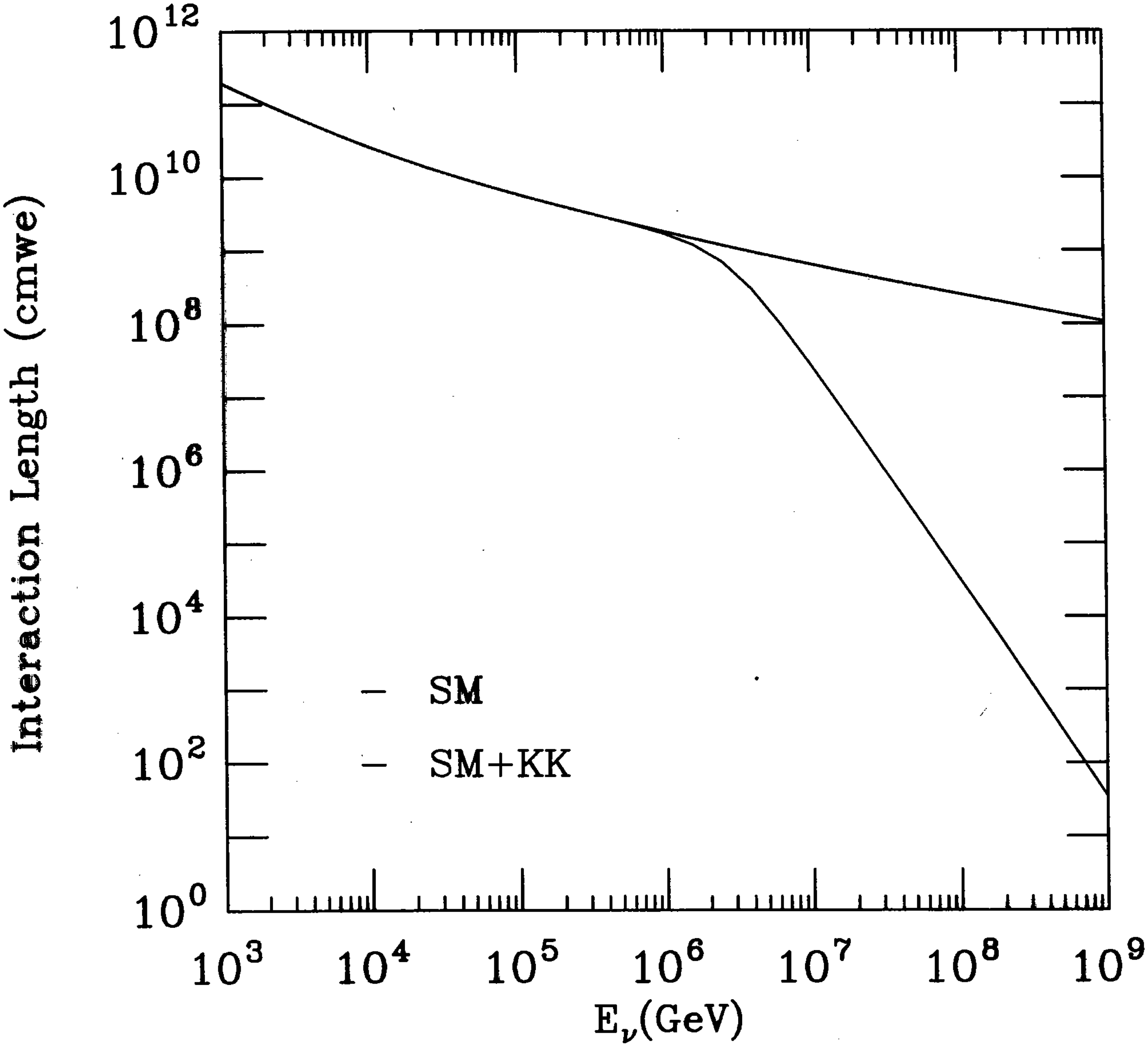
Iyer, Reno & I.S.



σ^{tot}
σ^{Gq}
σ^{Gg}
σ^{SM}
$\sigma^{G\bar{q}}$
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
σ(mb)
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
Energy (GeV)



σ^{tot}
σ^{Gq}
σ^{Gg}
σ^{SM}
$\sigma^{G\bar{q}}$
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
σ(mb)
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
Energy (GeV)



Interaction Length (cmwe)
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
— SM
— SM+KK
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
E_ν(GeV)

Jain, McKay, Panda & Ralston
Phys. Lett. B484 (2000) 267

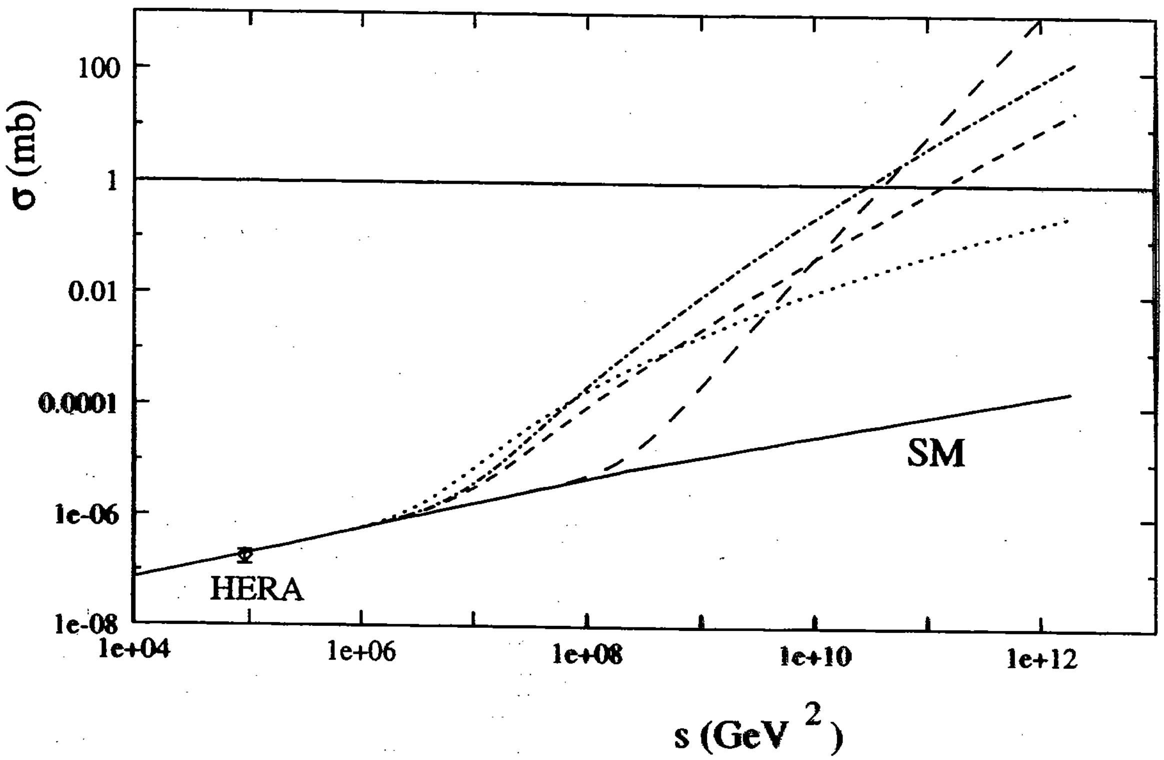


Figure 1: The νN cross section in the Standard Model (SM) compared to a theory with large extra dimensions and three different models for the unitarity extrapolation between perturbative to non- perturbative regimes. The dotted line shows the $log(s)$ growth case with $M_S = 1$ TeV and $\xi = 10$. The short dashed and dash-dotted lines show s^1 growth with $M_S = 1$ TeV and $\beta = 1$ and 0.1 respectively. The long dashed line shows s^2 growth with $M_S = 3$ TeV and $\beta = 1$. The contribution from massive graviton exchange is negligible at low energies but rises above the SM contribution when $\sqrt{s} > M_S$, reaching typical hadronic cross sections at incident neutrino energies in the range 5×10^{19} to 5×10^{20} GeV. The HERA data point is shown for comparison. The approximate minimum value required for νN cross-section, $\sigma = 1$ mb, is indicated by the horizontal straight line.

"String Excitations"

Cornet, Illana, Masip

PRL 86 (2001) 4235

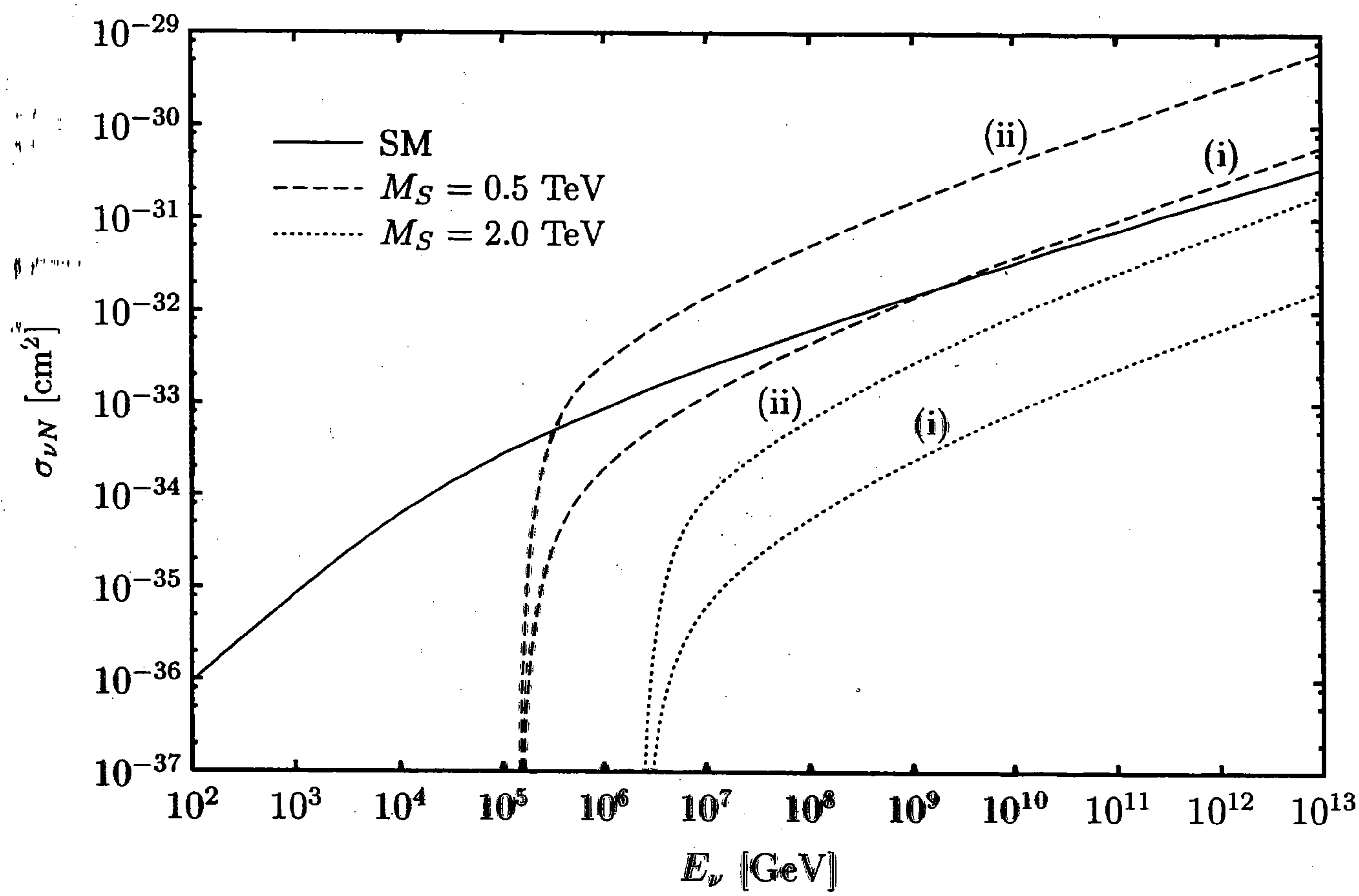


Figure 1: Neutrino-nucleon cross section versus the incident neutrino energy E_ν. The SM contribution (solid) includes neutral and charged current interactions. We plot the SR contribution for $M_S = 0.5$ TeV (dashes) and $M_S = 2$ TeV (dots) for the cases (i) $a = a' = b = b' = 0$ and (ii) $a = a' = b = b' = 5$.

SEE TAO HAN'S TALK

UHE Neutrinos as Probes of New Physics

- Even before the LHC, new TeV-scale physics may be observed in the scattering of ultrahigh energy ($E_\nu >$ 100TeV) cosmic or extragalactic neutrinos off nuclei in air or ice and detected by neutrino telescopes such as AMANDA, ICECUBE or RICE or by balloon experiment, such as ANITA or with cosmic ray air shower detectors such as Pierre Auger or AGASA or with the satellite experiments, such as EUSO and OWL.

- Possibility that we live in $4+n$ spacetime dimensions has profound implications. If gravity propages in these extra dimensions, the fundamental Planck scale, M_D, at which gravity becomes comparible in strength to other forces, may be far below $M_{Pl} \sim 10^{19}$ GeV, in TeV range, leading to a host of potential signatures for high energy physics $\Rightarrow$ one of the most striking consequences of low-scale gravity is the possibility of black hole creation in high-energy particle collisions.

- Most gravitation processes, such as those involving graviton emission and exchange, analyses rely on a perturbative description that breaks down for energies of M_D and above.

- In contrast, black hole properties are best understood for energies above M_D, where semiclassical and thermodynamic descriptions become increasingly valid.

- Particle scattering at super-Planckian energies is dominated in the s-channel by black hole production. Thus, black holes provide a robust probe of extra dimensions and low-scale gravity, as long as particle collisions with energies above M_D are available.

- Copious production of microscopic black holes is one of the least model-dependent predictions of TeV-scale gravity scenarios.

- Ultrahigh energy neutrinos $(E_\nu > 100$ TeV) can provide unique probe of the large extra spacetime dimensions $\Rightarrow$ detection of the black hole formation in neutrino interactions would reveal the structure of the extra dimensions on scales large as compared to the Planck scale.

Astrophysical and Cosmological Contraints:

- Supernova cooling
- Neutron Star heat excess
- Cosmology (Cosmic Microwave Background Radiation and Cosmic Gamma-Ray Background Radiation – cooling rate)

$M_\star > 600$TeV for $n = 2$

$M_\star > 30$TeV for $n = 3$

Astrophysical and Cosmological Constraints imply that $n = 2$ and $n = 3$ are ruled out!

Collider Limits:

- Fermilab:

  $M_\star > 530\text{GeV}$ for $n = 4$

  $M_\star > 580\text{GeV}$ for $n = 6$

  $M_\star > 680\text{GeV}$ for $n = 8$

- LEPII:

  $M_\star > 680\text{GeV}$ for $n = 4$

  $M_\star > 510\text{GeV}$ for $n = 6$

  $M_\star > 411\text{GeV}$ for $n = 8$

Black Holes in General Relativity

- Schwarzschild solution to Einstein's general relativity equations applied to a static massive object has a singularity at a Schwartzschild radius. If the radius of the object is less than R_S, a black hole with the event horizon at R_S is formed.
- According to Hawking, black holes are unstable semi-classically and evaporate, i.e. decay into thermal spectrum of particles.
- As the BH evaporates, its mass becomes smaller and the Hawking temperature increases.

Black Holes in Higher Dimensional Space-Time

- Static BH solution in N+1 dimensions is a generalization of familiar Schwarzschild solution

  Myers and Perry, Annals of Phys. **172**, 304 (1986).
- BH radiates mainly on the brane

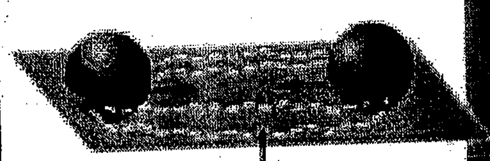
  Emparan, Horowitz and Myers, PRL 85, 499 (2000).

The New York Times ON THE WEB

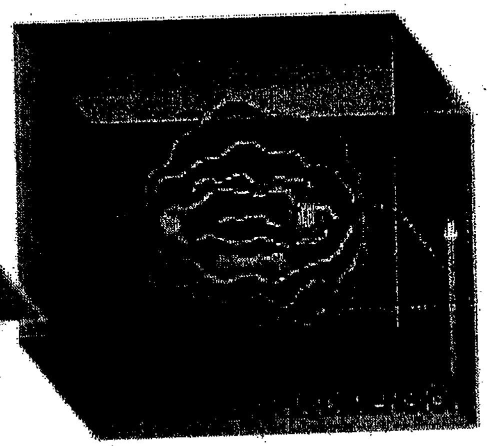
Black Holes on Demand

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

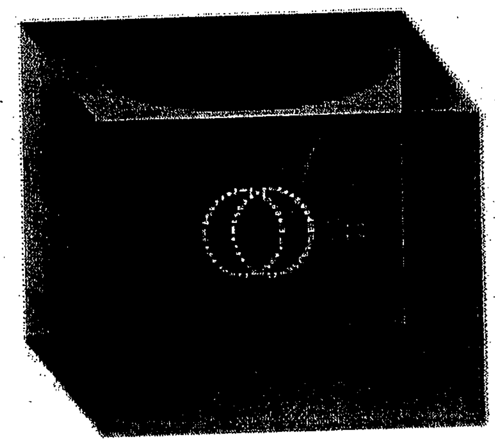
Particles collide in three dimensional space, shown below as a flat plane.



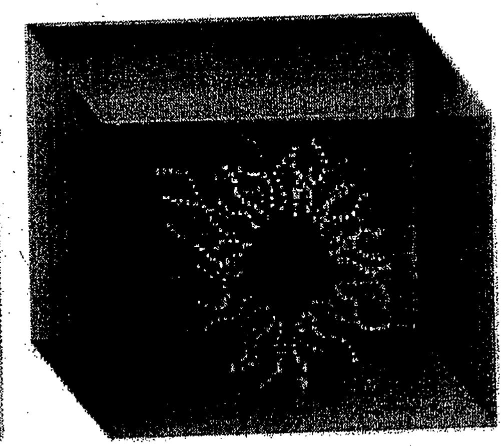
As the particles approach in a particle accelerator, their gravitational attraction increases steadily.



When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.



The extra dimensions would allow gravity to increase more rapidly so a black hole can form.



Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Black Hole Production and Decay

- In a high energy parton-parton collision, when the impact parameter is smaller than the Schwarzschild radius in d dimensions, a d-dimensional black hole is formed with the geometrical cross-section,

$$\sigma_{BH} = \pi r_S^2 (M_{BH} = \sqrt{\hat{s}}) \theta(\sqrt{\hat{s}} - M_{BH}^{min})$$

where r_S is Schwarzschild radius in d dimensions given by

$$r_S = \frac{1}{\sqrt{\pi}} \frac{1}{M_P} [\frac{M_{BH}}{M_P} (\frac{8\Gamma(\frac{n+3}{2})}{n+2})]^{\frac{1}{n+1}}$$

and $\sqrt{\hat{s}}$ is the center of mass energy of parton-parton collision.

- The cross-section for black hole production in pp collisions, for example, is obtained by folding in the parton densities:

$$\sigma(pp \to BH + X) = \frac{1}{s} \sum_{ab} \int_{M^2_{BH,min}}^{s} dM^2_{BH}$$
$$\times \int_{x_{1,min}}^{1} \frac{dx_1}{x_1} f_a(x_1, Q^2) \hat{\sigma}_{BH} f_b(x_2, Q^2)$$

- Radiation rate into Standard Model particles is given by a thermal distribution in 4 dimensions:

$$\frac{dE}{dt} = \frac{1}{(2\pi)^3} \sum_i \int \frac{\omega g_i \sigma_i d^3k}{e^{\omega/T_{BH}} \pm 1}$$

with $T_{BH} = \frac{d-3}{4\pi r_S}$, g_i ia a statistical factor, acounting for the number of degrees of freedom that can be produced. The sign $+$ is for fermions and $-$ for bosons, σ_i are the gray body factors, $\sigma_i \approx \Gamma_s A_4$, where Γ_s are constant ($\Gamma_{1/2} = 2/3, \Gamma_1 = 1/4, \Gamma_0 = 1$).

- A black hole acts as an absorber with a radius somewhat larger than r_S, such that A_n is given by

$$A_n = \Omega_{n-2}\left(\frac{d-1}{2}\right)^{\frac{d-2}{d-3}}\left(\frac{d-1}{d-3}\right)^{\frac{n-2}{2}} r_S^{n-2}$$

Emparan, Horowitz, Myers, PRL 85, 499 (2000).

- For the emission into gravitons, which are d-dimensional, the rate is given by:

$$\frac{dE}{dt} = \frac{1}{(2\pi)^{d-1}}\sum_i \int \frac{\omega g_i \sigma_i d^{d-1}k}{e^{\omega/T_{BH}} - 1}$$

where $\sigma_i \sim A_{d-1}$. This rate is much smaller than emission rate into SM particles.

- The lifetime of the black hole is then obtained by integrating rate equation and, assuming no mass evolution during the decay, is given by:

$$\tau_{BH} = M_{BH}\left[\frac{\pi^2}{30}\left(\sum_f \frac{7}{8} g_f \sigma_f + \sum_b g_b \sigma_b\right) T_{BH}^4\right]^{-1}$$

- The energy radiated in n dimensions by a d-dimensional black hole with temperature T is

$$\frac{\mathrm{d}E_n}{\mathrm{d}t} \simeq \int \frac{\omega^{n-1} d\omega A_n}{e^{\omega/T} - 1}$$

where A_n is the area of the black hole in n dimensions,

$$A_n = \Omega_n r_S^n \quad T = \frac{d-3}{4\pi r_S} \qquad \Omega_{n-1} = \frac{2\pi^{n/2}}{\Gamma(n/2)}$$

Ω_n is the volume of a unit n sphere

$$\frac{\mathrm{d}E_n}{\mathrm{d}t} \simeq \frac{1}{(2\pi)^{n-1}} \Gamma(n)\zeta(n)\Omega_{n-2}^2 \left(\frac{d-3}{4\pi}\right)^n \frac{1}{r_S^2}$$

- The black hole is a d-dimensional object and it radiates in all dimensions with a rate $\mathrm{d}E_n/\mathrm{d}t$. However, Standard Model fields are four dimensional fields that live on the brane, thus the rate of emission on the brane is $\mathrm{d}E_4/\mathrm{d}t$.
- The ratio of emission rates in 4 dimensions and in n dimensions is:

$$\frac{\mathrm{d}E_4/\mathrm{d}t}{\mathrm{d}E_n/\mathrm{d}t} \sim 10$$

thus most of the radiation is on the brane, in SM particles.

Assumptions:

- To avoid stringy effects and be able to use semi-classical approach we consider $M_{BH} >> M_D$
- Decay: BH evaporation at the original temperature
- BH radiates mainly on the brane
- Most of the decay is hadronic
- Typical lifetime 10^{-27} s.
- Lack of knowledge of quantum gravity effect close to the Planck scale – theoretical input needed
- Greybody factors recently calculated in $\omega r_S << 1$ approximation

Kanti and March-Russell, hep-ph/0212199

Black Hole Production by UHE Neutrinos

- Black hole can be produced in scattering of UHE neutrinos on nucleons in the atmosphere or in the Earth. The neutrino-nucleon cross section for black hole production is given by

$$\sigma(\nu N \to \mathrm{BH}) = \sum_i \int_{M_{BH}^{\mathrm{min}}}^{1} dx \;\hat{\sigma}_i(xs)\; f_i(x, Q^2),$$

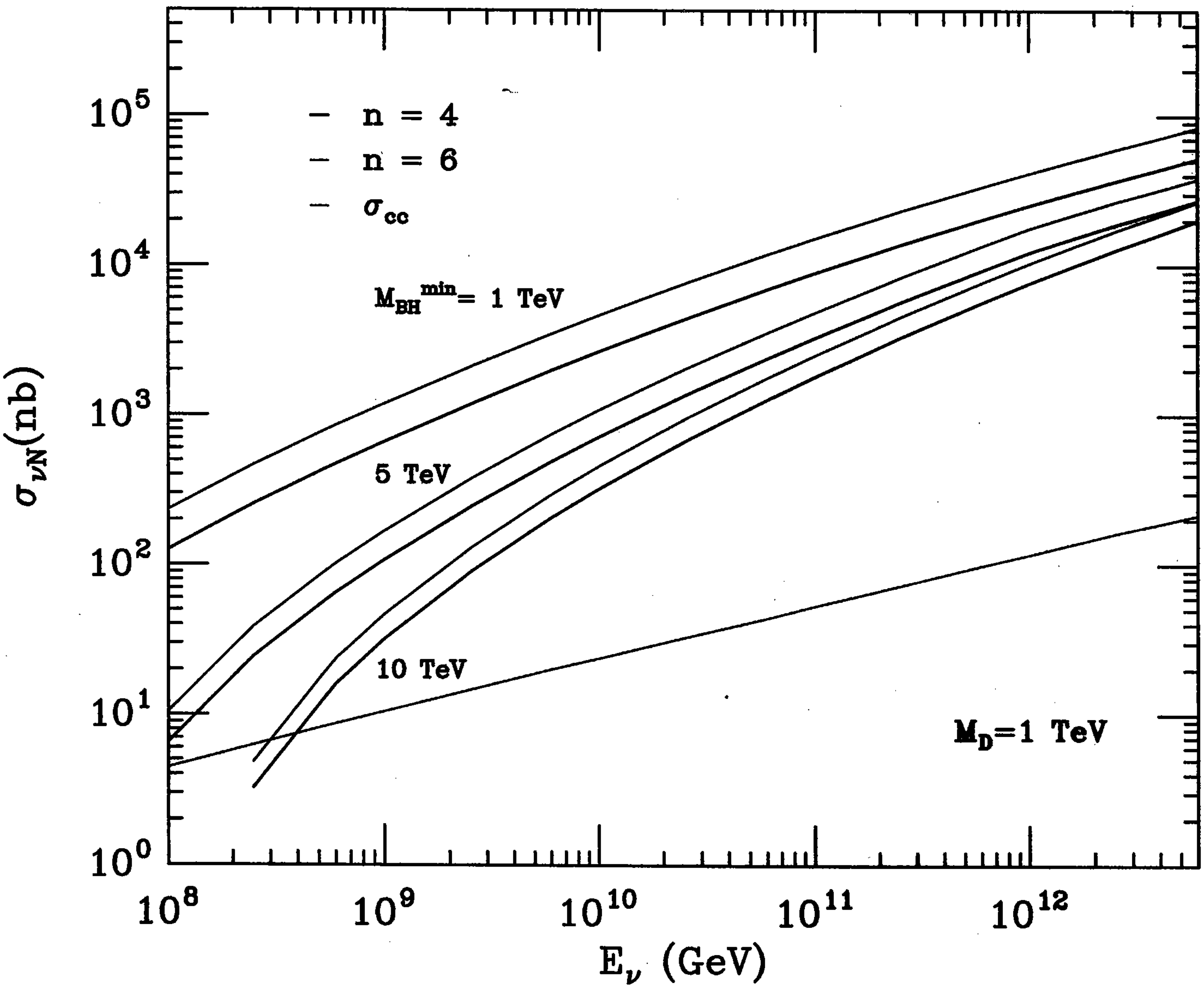
where

$$\hat{\sigma}_i = \pi r_S^2 (M_{BH} = \sqrt{\hat{s}}) \theta(\sqrt{\hat{s}} - M_{BH}^{min}),$$

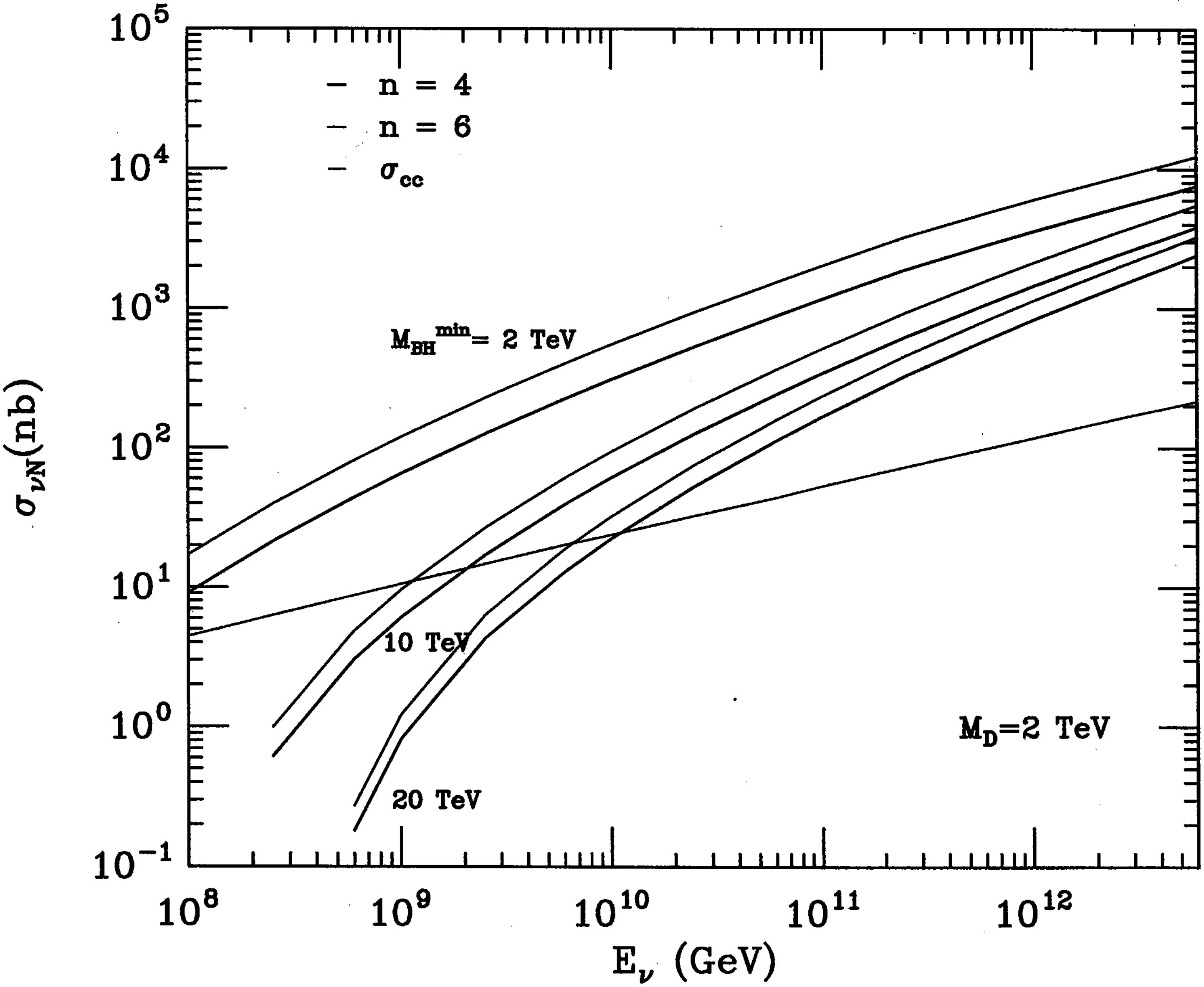
$\hat{s} = xs$, s is the center of mass energy, $s = 2m_N E_\nu$

$f_i(x, Q^2)$'s are parton distribution functions

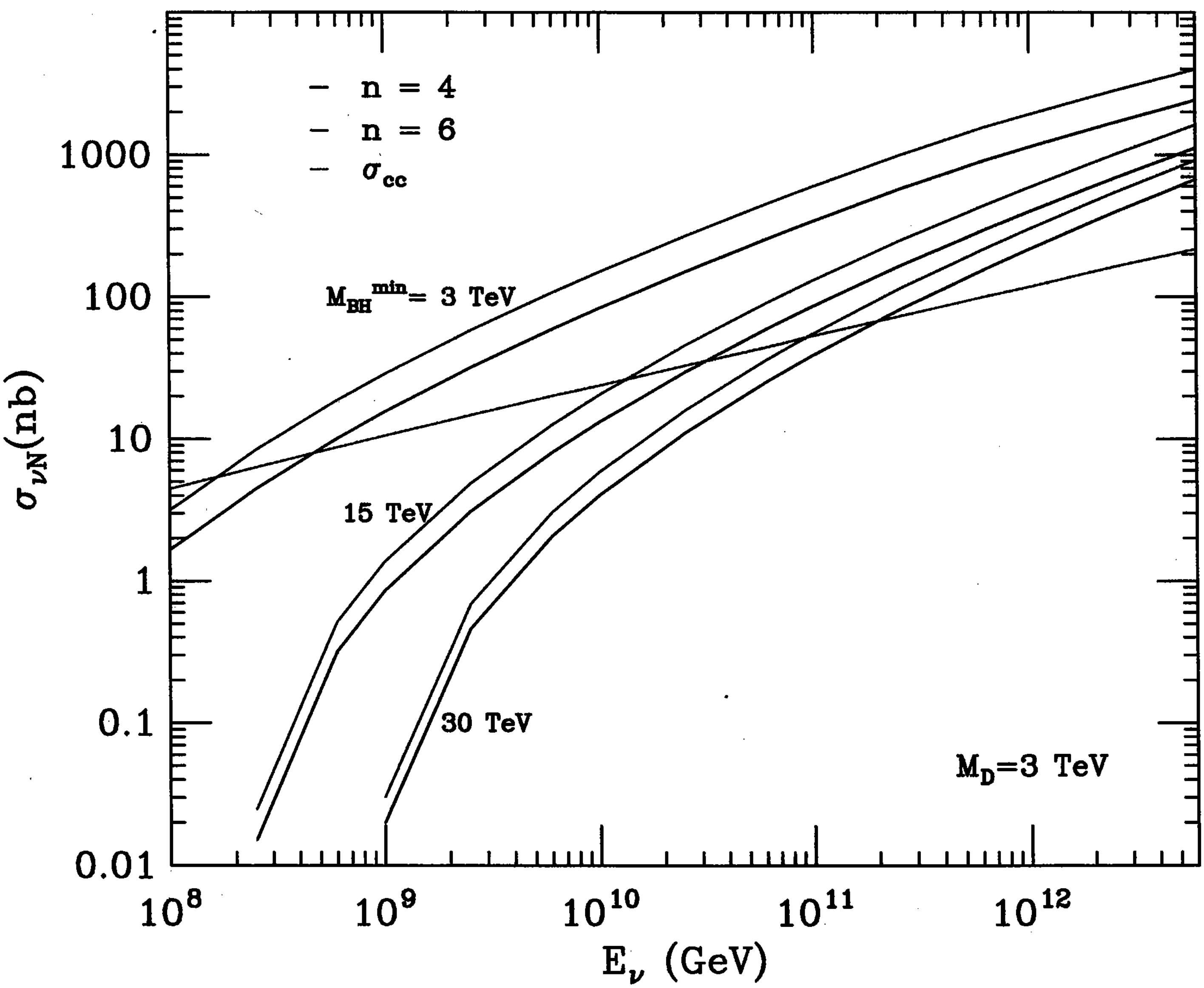
M_{BH}^{min} is the minimum black hole mass for which semiclassical approximation above is valid ($M_{BH}^{\mathrm{min}} >> M_D$)



n = 4
n = 6
σ_{cc}
M_{BH}^{min}= 1 TeV
5 TeV
10 TeV
M_D=1 TeV
$\sigma_{\nu N}$(nb)
E_ν (GeV)
10^0
10^1
10^2
10^3
10^4
10^5
10^8
10^9
10^{10}
10^{11}
10^{12}



n = 4
n = 6
σ_{cc}
M_{BH}^{min}= 2 TeV
10 TeV
20 TeV
M_D=2 TeV
$\sigma_{\nu N}$(nb)
E_ν (GeV)
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^8
10^9
10^{10}
10^{11}
10^{12}



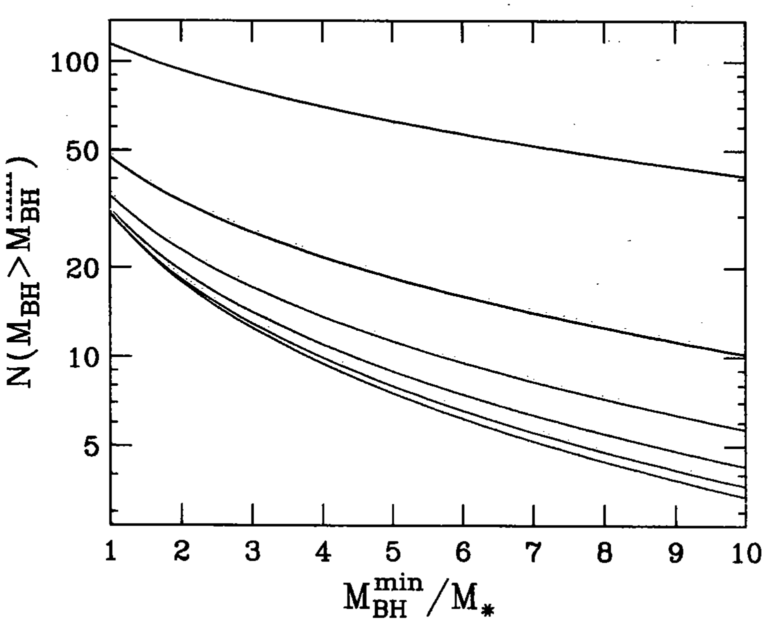
n = 4
n = 6
σ_{cc}
M_{BH}^{min}= 3 TeV
15 TeV
30 TeV
M_D=3 TeV
$\sigma_{\nu N}$(nb)
E_ν (GeV)
0.01
0.1
1
10
100
1000
10^8
10^9
10^{10}
10^{11}
10^{12}

Black Holes in Cosmic Rays

Feng and Shapere, PRL **88** (2002) 021303.
Anchordoqui, Feng, Goldberg and Shapere,
PR **D65** (2002) 124027.

- Limits from non-observation of horizontal showers by the Fly's Eye Collaboration and Akeno Giant Air Shower Array (AGASSA): $M_D \approx 1$TeV -1.4 TeV excluded for $n \geq 4$.

- Detect BH in the Pierre Auger fluorescence experiment or AGASSA $\Rightarrow$ few to a hundred BHs can be detected before the LHC turns on. If no black holes are found then $M_D = 2$ TeV is excluded for any n.



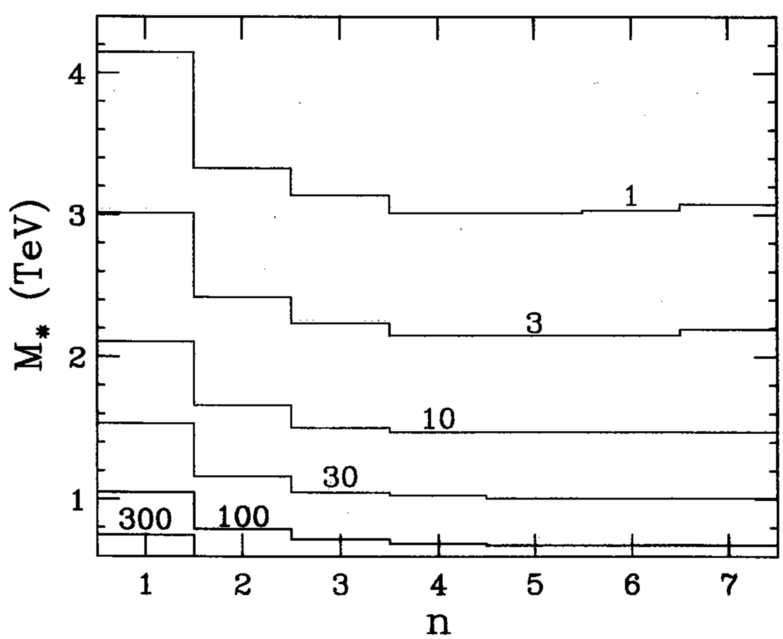


Figure 1: The number of BH events detected in 5 Auger site-years a) $M_\star = 1$TeV; b) $M_\star = M_{BH}^{min}$

Black Holes in Neutrino Telescopes

Alvarez-Muniz, Feng, Halzen, Tan and Hooper, PRD **65**, 124015 (2002)
Kowalski, Ringwald and Tu, PL **B529**, 1 (2002)
Dutta, Reno and Sarcevic, PR **D66**, 033002 (2002)

- The contained event rate for black hole production is

$$Rate = \int dE_\nu N_A V_{eff}\, \sigma_{BH}(E_\nu) \frac{dN_\nu}{dE_\nu}$$

N_A is Avogadro's number

$\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}}$ is the neutrino flux that reaches the detector

V_{eff} is the effective volume of the detector.

Event Rates for ICECUBE

Contained event rates per year for $M_D = 1$ TeV ($m = M_{BH}^{min}/M_D$) and $E_{shr}^{min} = 10^8$ GeV.

n = 4

m	E^{-1}	E^{-2}	GRB_{WB}	TD_{WMB}	TD_{SLSC}	AGN_{M95}	AGN_{SS}	COS_{STD}	COS_{STR}
1	5447.0	444.3	0.481	56.01	0.563	32.73	9.348	2.16	5.89
2	2430.0	225.0	0.206	34.30	0.285	15.96	3.767	1.19	3.16
3	1363.0	141.1	0.112	24.77	0.177	9.65	1.923	0.79	2.06
4	848.2	97.9	0.067	19.26	0.121	6.45	1.082	0.57	1.47
5	560.0	72.0	0.043	15.65	0.088	4.57	0.636	0.43	1.11

n = 6

1	9930.0	797.9	0.879	97.46	1.013	59.14	17.190	3.85	10.50
2	4161.0	378.8	0.355	55.99	0.481	27.07	6.514	1.98	5.29
3	2250.0	228.5	0.186	38.92	0.288	15.76	3.210	1.26	3.32
4	1364.0	154.0	0.109	29.45	0.192	10.25	1.762	0.89	2.31
5	881.7	110.9	0.068	23.42	0.137	7.12	1.016	0.66	1.71
SM	136	8.4	0.01	0.65	0.01	0.6	0.3	0.03	0.09

Contained event rates per year for $M_D = 2\text{TeV}$ and $E_{shr}^{min} = 10^8$ GeV.

n = 4

m	E^{-1}	E^{-2}	GRB_{WB}	TD_{WMB}	TD_{SLSC}	AGN_{M95}	AGN_{SS}	COS_{STD}	COS_{STR}
2	460.3	42.63	0.39E-01	6.50	0.54E-01	3.023	0.71E+00	0.225	0.599
4	160.7	18.54	0.13E-01	3.65	0.23E-01	1.222	0.21E+00	0.108	0.279
6	72.7	10.47	0.54E-02	2.48	0.13E-01	0.639	0.72E-01	0.065	0.165
8	36.2	6.68	0.24E-02	1.85	0.77E-02	0.375	0.23E-01	0.044	0.109
10	19.9	4.65	0.12E-02	1.45	0.51E-02	0.238	0.91E-02	0.031	0.077

n = 6

2	853.3	77.67	0.73E-01	11.48	0.99E-01	5.551	0.13E+01	0.406	1.085
4	279.7	31.59	0.22E-01	6.04	0.39E-01	2.103	0.36E+00	0.182	0.474
6	121.9	17.11	0.90E-02	3.95	0.21E-01	1.058	0.12E+00	0.106	0.269
8	58.9	10.59	0.39E-02	2.86	0.12E-01	0.604	0.39E-01	0.069	0.173
10	31.8	7.19	0.20E-02	2.19	0.80E-02	0.375	0.15E-01	0.048	0.119
SM	136	8.4	0.01	0.65	0.01	0.6	0.3	0.03	0.09

Contained event rates per year for $M_D = 3$TeV and $E_{shr}^{min} = 10^8$ GeV.

n = 4

m	E^{-1}	E^{-2}	GRB_{WB}	TD_{WMB}	TD_{SLSC}	AGN_{M95}	AGN_{SS}	COS_{STD}	COS_{STR}
3	97.6	10.11	0.80E-02	1.77	0.13E-01	0.691	0.14E+00	0.56E-01	0.15E+00
6	27.5	3.96	0.20E-02	0.94	0.48E-02	0.241	0.27E-01	0.25E-01	0.62E-01
9	9.9	2.08	0.61E-03	0.62	0.24E-02	0.112	0.47E-02	0.14E-01	0.34E-01
12	4.4	1.30	0.23E-03	0.45	0.13E-02	0.061	0.66E-03	0.88E-02	0.22E-01
15	2.0	0.88	0.98E-04	0.34	0.81E-03	0.035	0.11E-03	0.60E-02	0.14E-01
n = 6									
3	182.6	18.55	0.15E-01	3.16	0.23E-01	1.280	0.26E+00	0.10E+00	0.27E+00
6	48.2	6.77	0.36E-02	1.56	0.82E-02	0.419	0.49E-01	0.42E-01	0.11E+00
9	16.6	3.42	0.10E-02	0.98	0.39E-02	0.187	0.80E-02	0.23E-01	0.56E-01
12	7.1	2.06	0.38E-03	0.70	0.22E-02	0.099	0.11E-02	0.14E-01	0.34E-01
15	3.2	1.36	0.16E-03	0.52	0.13E-02	0.056	0.17E-03	0.94E-02	0.22E-01
SM	136	8.4	0.01	0.65	0.01	0.6	0.3	0.03	0.09

Detection of Black Holes with OWL

Dutta, Reno and Sarcevic, PR **D66**, 033002 (2002)

The event rate for black hole production with OWL is given by

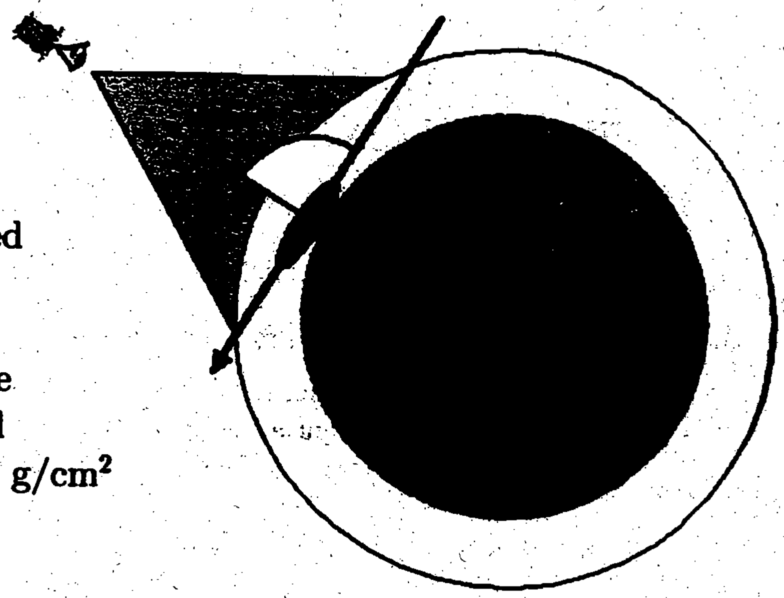
$$N = \int A(E_\nu) \frac{dN}{dE_\nu} \sigma_{BH}(E_\nu) dE_\nu$$

where

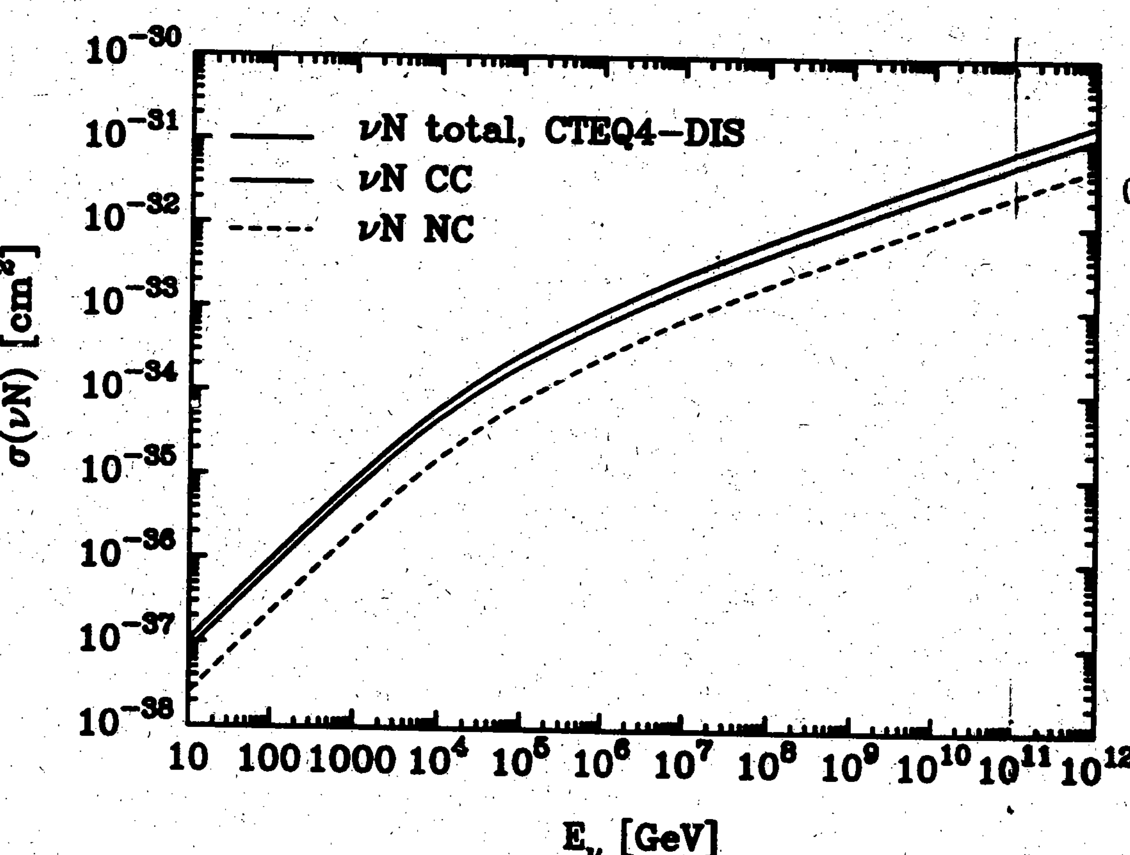
$A(E_\nu)$ is the OWL effective aperture
$\frac{dN}{dE_\nu}$ is the neutrino flux
$\sigma_{BH}(E_\nu)$ is the cross section for the production of black hole.

Large Aperture (10^{13} mtons of atmospheric target) opens the door for observing ultra-high energy neutrinos interactions

Value of $\sigma_{CC}(\nu_\lambda N \to \lambda N')$
$\longrightarrow \lambda_\nu \sim 10^{10}$ cm
(Air, STP, $E_\nu = 10^{20}$ eV)



$\rightarrow$ Horizontal Airshowers initiated deep (> 1500 g/cm^2) in the atmosphere provide a signature of neutrino interactions which are well-separated from hadronic and electromagnetic showers, $\lambda_p \sim 50$ g/cm^2 (Air, STP, $E_p = 10^{20}$ eV)



@ 10^{20} eV

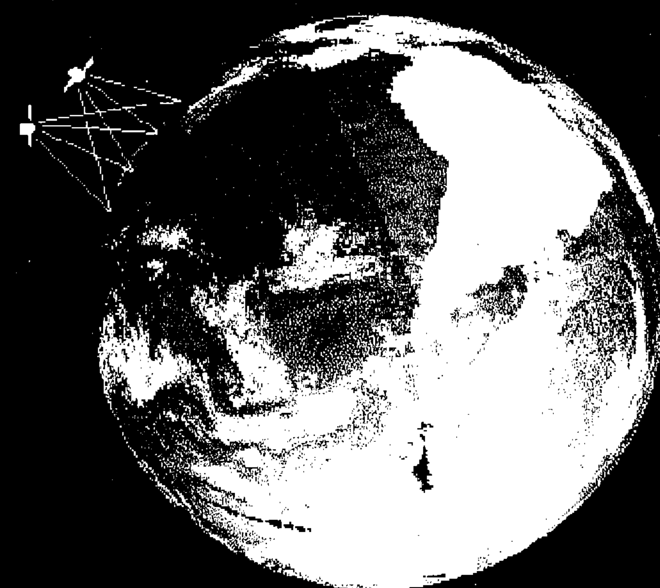
$\sigma_{TOT} \sim 8 \cdot 10^{-32}$ cm^2

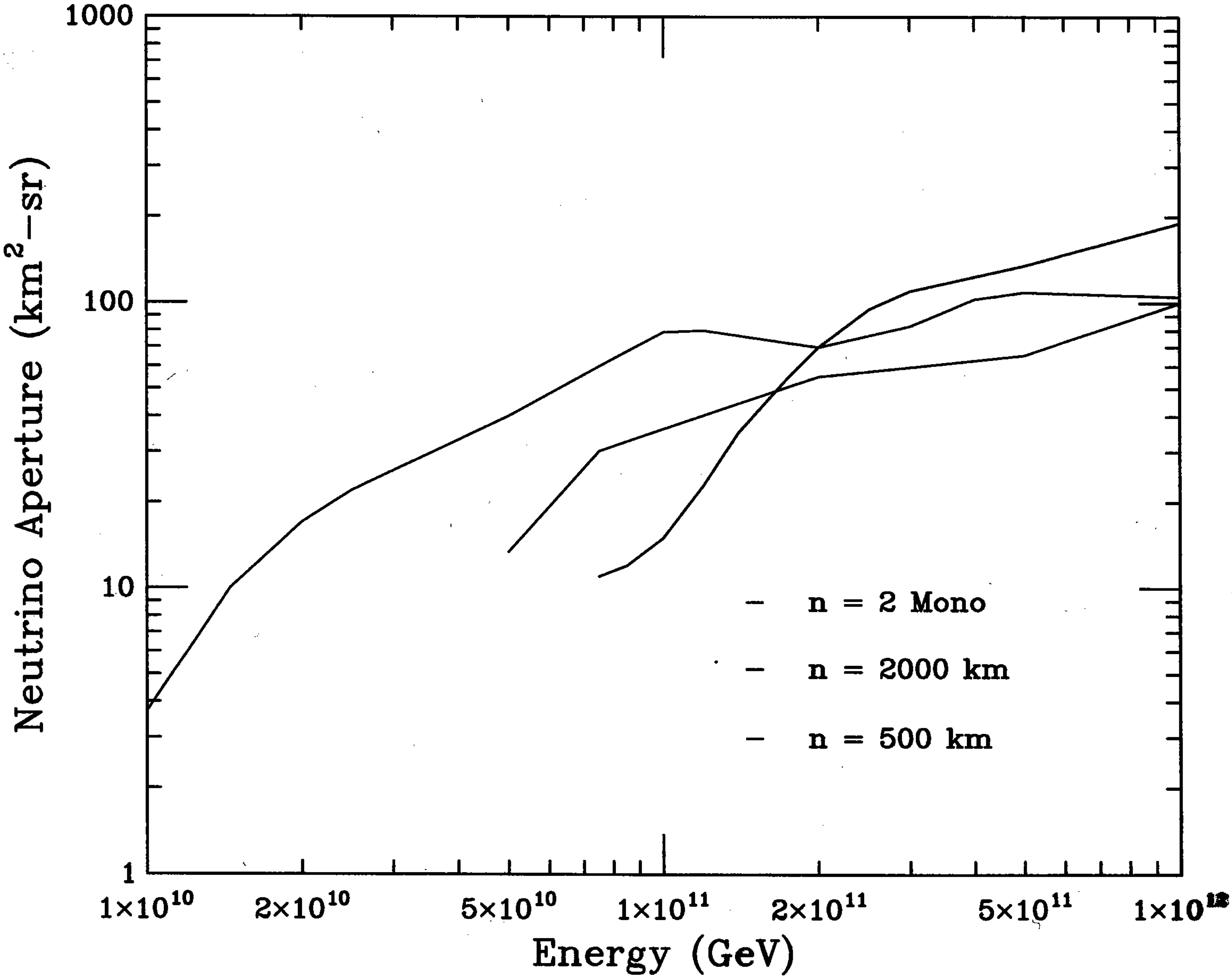
Gandhi et al., PHYS. REV D 58, 093009

Orbiting Wide- angle Light collectors (OWL)

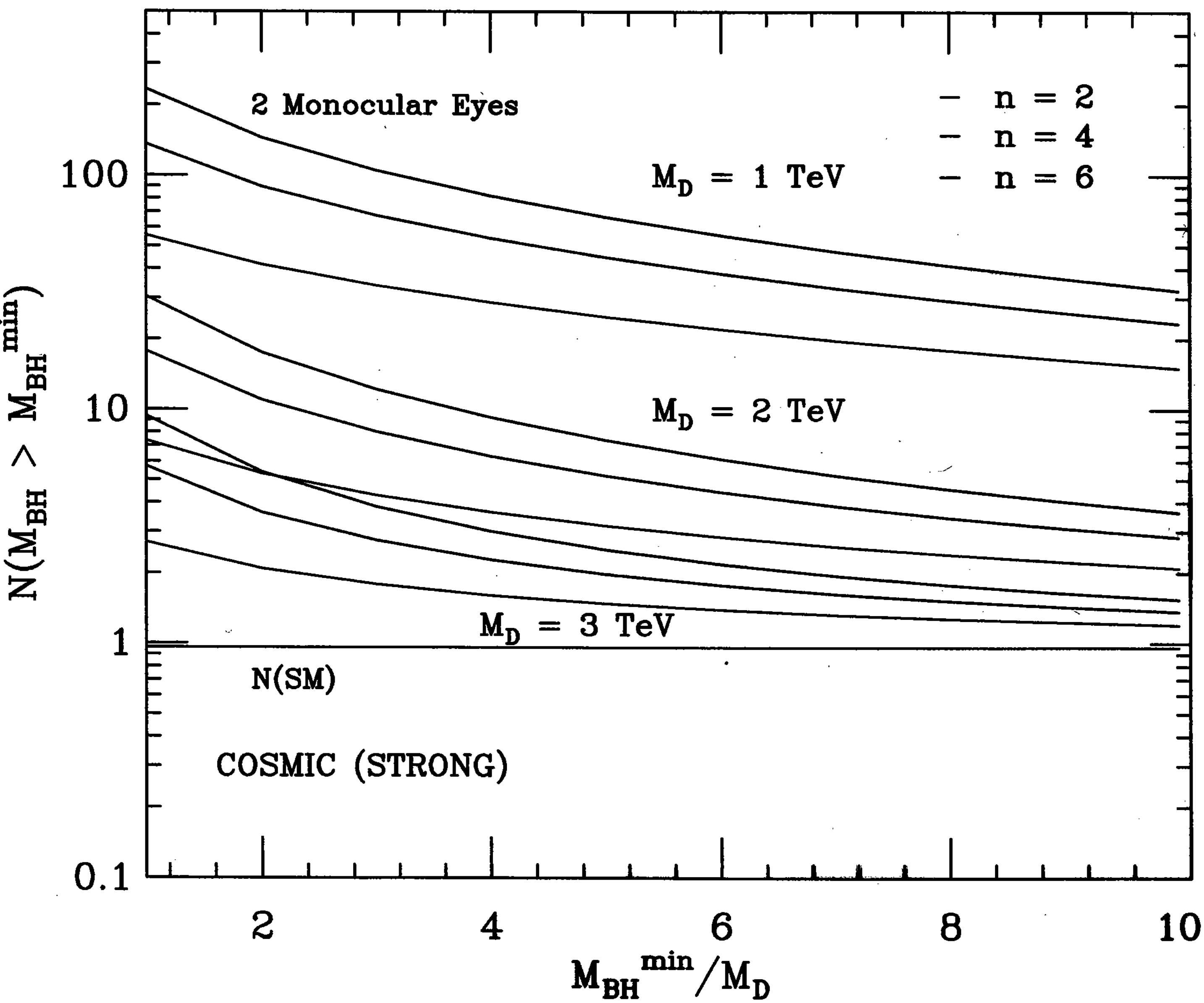
An Earth Orbiting System to Study Air Showers Initiated by $>10^{19}$ eV Particles

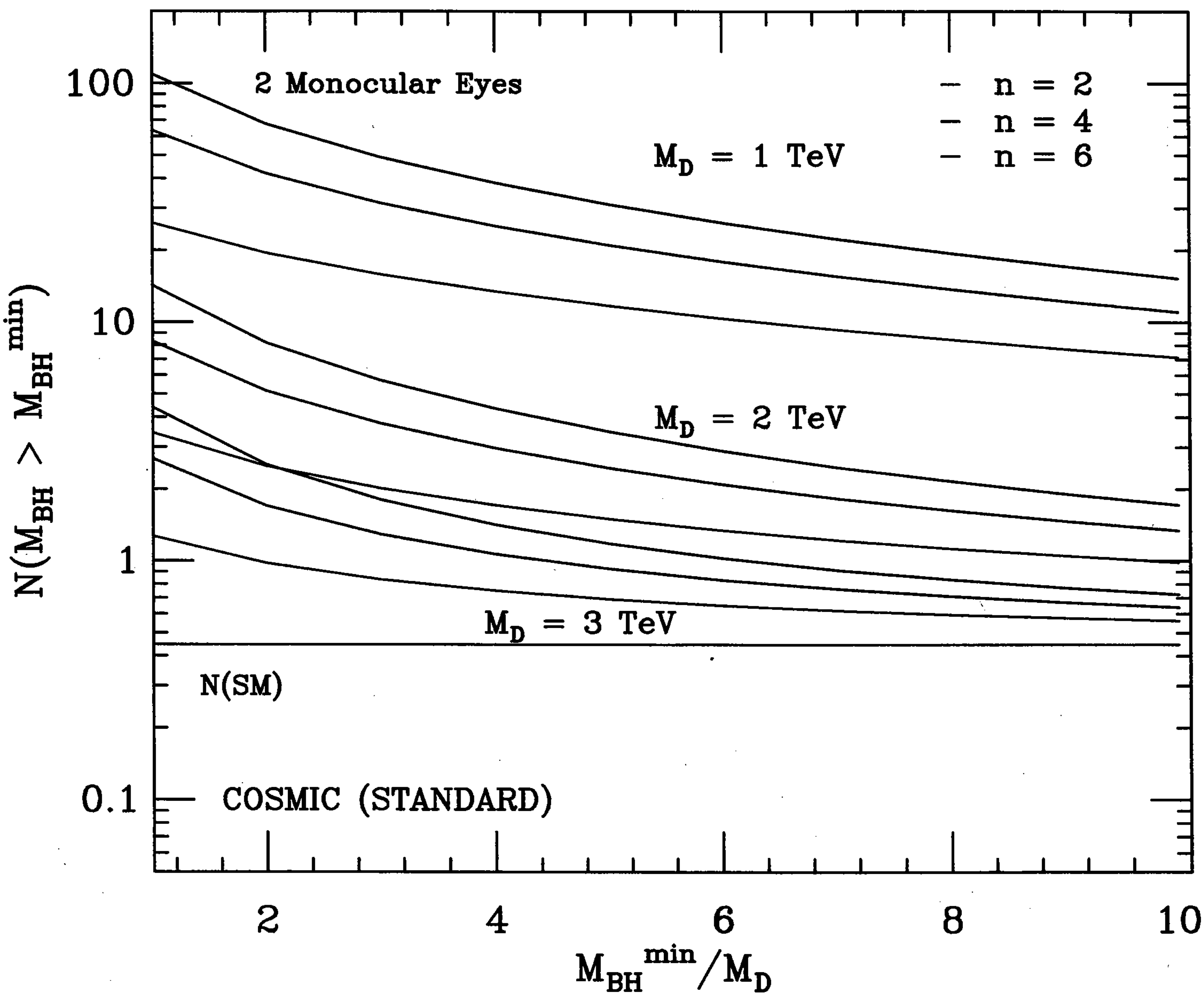
- *Earth as calorimeter*
- *Nitrogen fluorescence*
- *Monitor 3 million Km^2*
- *3000 events/year*



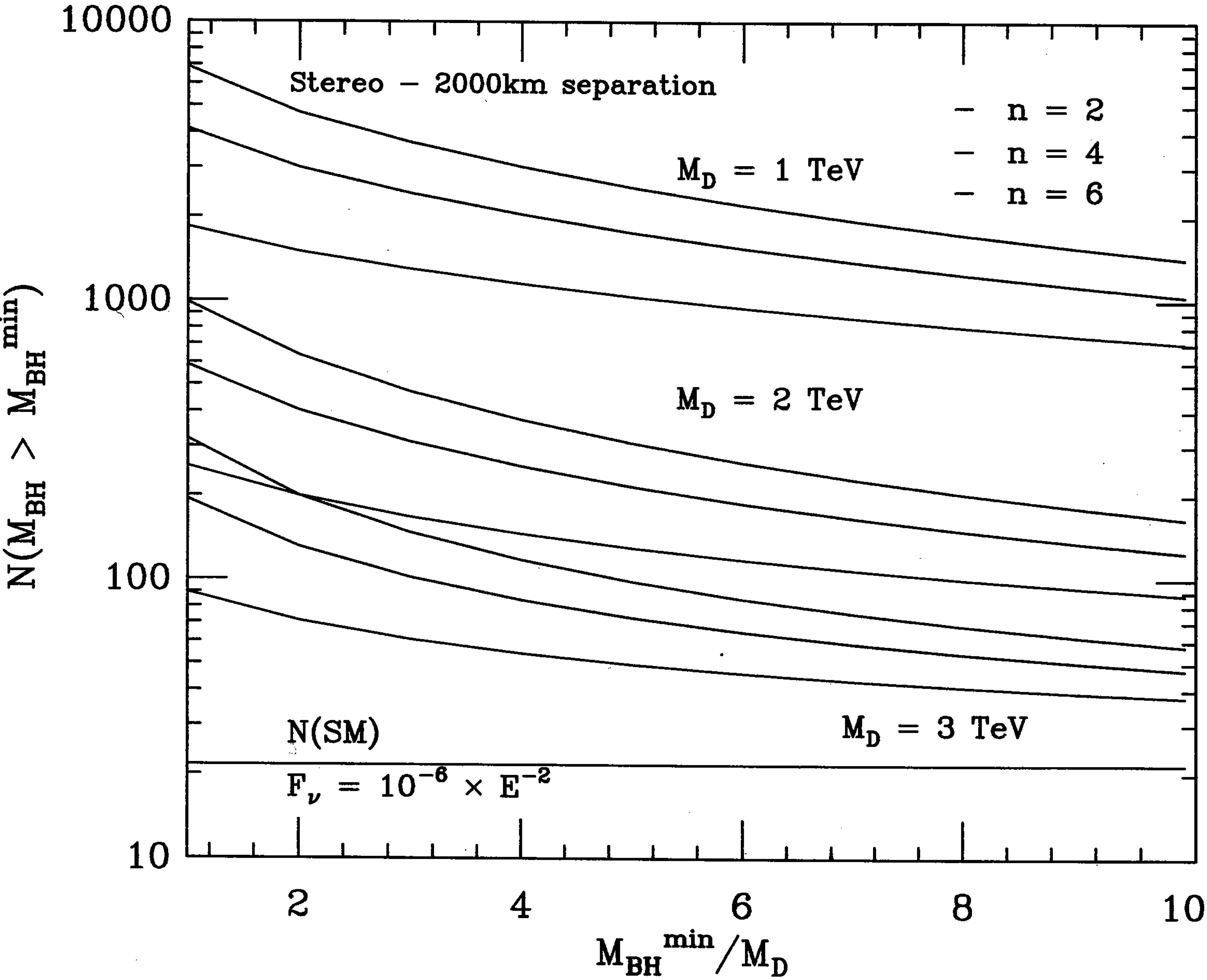


Neutrino Aperture (km^2–sr)
1000
100
10
1
Energy (GeV)
1×10^{10}
2×10^{10}
5×10^{10}
1×10^{11}
2×10^{11}
5×10^{11}
1×10^{12}
n = 2 Mono
n = 2000 km
n = 500 km


2 Monocular Eyes
n = 2
n = 4
n = 6
M_D = 1 TeV
M_D = 2 TeV
M_D = 3 TeV
N(SM)
COSMIC (STRONG)
100
10
1
0.1
2
4
6
8
10
$N(M_{BH} > M_{BH}^{min})$
M_{BH}^{min}/M_D



2 Monocular Eyes
n = 2
n = 4
n = 6
M_D = 1 TeV
M_D = 2 TeV
M_D = 3 TeV
N(SM)
COSMIC (STANDARD)
100
10
1
0.1
2
4
6
8
10
$N(M_{BH} > M_{BH}^{min})$
M_{BH}^{min}/M_D



Stereo – 2000km separation
– n = 2
– n = 4
– n = 6
M_D = 1 TeV
M_D = 2 TeV
M_D = 3 TeV
N(SM)
$F_\nu = 10^{-6} \times E^{-2}$
10000
1000
100
10
2
4
6
8
10
$N(M_{BH} > M_{BH}^{min})$
M_{BH}^{min}/M_D

- UHE neutrino interactions can probe physics scales above TeV $\Rightarrow$ potential for discovering physics beyond the Standard Model.

- Production of black holes in νN interactions exceeds Standard Model cross section at energies above 10^8 GeV for $M_D \geq 2$TeV and $n \geq 2$.

- Black Holes in Cosmic Rays: Limits from Fly's Eye and AGASSA, $M_D \approx 1$TeV -1.4 TeV excluded for $n \geq 4$. Pierre Auger experiment can probe $M_D \leq 2$ TeV for any n.

- Black Holes with Neutrino Telescopes: ICECUBE rates for BH detection are promising for AGN and TD Models (for $M_D \leq 2$TeV, $n \geq 2$) but rates for cosmogenic neutrinos are too small.

- OWL could potentially probe the fundamental Planck scale up to $M_D = 3$TeV for $n \geq 2$.

Conclusion

- Kilometer-size neutrino telescope has a very good chance of detecting extragalactic neutrinos with energy threshold of 10TeV or 100TeV.

- Extragalactic neutrino sources, such as AGN, GRB and TD can provide 1000 megaparsec baseline for studying $\nu_\mu \to \nu_\tau$ oscillations.

- ν_τ upward flux is enhanced and has distinct angular and energy dependence at the detector.

- Detection of ν_τ appearance:

  ⋆ Combined measurements of the upward muons and hadronic/em showers provide unambiguous signal of $\nu_\mu \to \nu_\tau$ oscillations independent of the theoretical uncertainties in the models of extragalactic neutrino sources.